UNITED STATES DEPARTMENT OF AGRICULTURE
OFFICE OF INFORMATION
DIVISION OF PUBLICATIONS

TECHNICAL BULLETINS

Nos. 326-350

WITH CONTENTS

PREPARED IN THE INDEXING SECTION

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1933

CONTENTS

TECHNICAL BULLETIN NO. 326.—BREEDING THE HONEYBEE UNDER CONTROLLED CONDITIONS (W. J. NOLAN): Page

Introduction 1
Status of work on breeding under controlled conditions 4
With natural insemination 4
With artificial insemination 5
Breeding work at the bee culture laboratory 11
Results of artificial insemination 12
On queens used in 1927, 1928, and 1929 12
On queens used in 1930 13
On queens used in 1931 and 1932 17
New instruments and methods for artificial insemination 21
Glass holder 21
Mount for glass holder 22
Spreading and holding abdominal tips 23
Multiple set-up 27
False stage 28
Pipette manipulator 28
Pipette 30
Use of an anesthetic 30
Filling the pipette 31
Mucus plug 31
Marking individuals 33
Drones 34
Obtaining drones 34
Determining sexual maturity of individual drones 35
Queen rearing and testing 36
Experiments in 1930 36
Apartment hives 37
Wintering in apartment hives 40
Queen rearing in 1931 41
Hive records 42
Visability of spermatozoa 42
Successive inseminations 43
Mixing sperm from different drones 44
Optimum age of queen for artificial insemination 44
Succession of generations 45
Summary 46
Literature cited 47

TECHNICAL BULLETIN NO. 327.—COST OF PUMPING FOR DRAINAGE IN THE UPPER MISSISSIPPI VALLEY (John B. Sutton):

Introduction 1
General description of plants studied 2
Collection and use of operation records 7
Pump ratings and tests 7
Original operation data 8
Explanation of tables 8
Determination of operating expenses 9
Fixed charges of interest and depreciation 9
Operating costs including fixed charges 14
Operation and cost records 15
Banner Special drainage and levee district 15
Coal Creek drainage and levee district 18
Green Bay drainage and levee district 23
Hartwell drainage and levee district 27

TECHNICAL BULLETIN No. 327—Continued.
Operation and cost records—Continued. Page
Hunt drainage and levee district 29
Indian Grave drainage and levee district 31
Lima Lake drainage and levee district 37
South Beardstown drainage and levee district 39
Bay Island drainage and levee district 44
Crane Creek drainage and levee district 49
Henderson County drainage and levee districts nos. 1 and 2 51
Scott County drainage and levee district 57
Eldred drainage and levee district 62
Fabius drainage and levee district 67
Mauvaisterre drainage and levee district 70
McGee Creek drainage and levee district 73
Valley City drainage and levee district 77
Summary of operation data 80
Average annual cost of pumping 83
Unit costs of pumping 86
Cost per brake horsepower-hour 87
Cost per acre-foot pumped 89
Cost per acre of watershed 90
Cost per acre assessed 91
Relation of cost of pumping to run-off depth 91
Backwater from dams 93
Application of data 94
Example 1 94
Example 2 96
Example 3 96
Factors affecting choice of power type 96
Summary and conclusions 98

TECHNICAL BULLETIN No. 328.—PEACH BROWN ROT (John W. Roberts and John C. Dunegan):
Introduction 1
History of the disease in the United States 2
Losses caused by the disease 5
Varietal susceptibility 6
The fungus causing the disease 6
Taxonomic position 6
Geographic distribution 12
Morphology 12
Strains or physiologic forms 16
Homothallism 17
Growth on artificial media 18
Enzyme production 18
Function of vitamins in the metabolism of the fungus 19
Temperature relations 20
Relation of hydrogen-ion concentration to growth 20
Viability of spores 21
Germination of spores 22
Dissemination of the fungus 24
Host plants 25
Seasonal life history and pathogenicity of *Sclerotinia fructicola* 26
Survival in winter 26
Occurrence of apothecia 28
Discharge of ascospores 30
The blossom-blight phase of the disease 31
The fruit-rot and mummy phase of the disease 32
The canker and twig-blight phase of the disease 33
Leaf infection 38
Relation of insect pests to infection 38
Pathological anatomy 40
Control of peach brown rot 42
Sanitary measures 42
Spraying and dusting 44
Fumigation 48
Summary 51
Literature cited 54

TECHNICAL BULLETIN No. 329.—EXPERIMENTS IN WHEAT PRODUCTION ON THE DRY LANDS OF OREGON, WASHINGTON, AND UTAH (David E. Stephens, H. M. Wanser, and Aaron F. Bracken):

Page

Importance of wheat in the far West 1
Soils 8
Climatic data 9
Precipitation 9
Evaporation 10
Temperature 10
Tillage experiments 11
Treatment of land before plowing 11
Plowing 16
Substitutes for plowing 32
Cultivation of summer fallow 33
Tillage factors influencing yields and quality of winter wheat 42
Harrowing the growing crop 44
Rate and date of seeding experiments 47
Results at Moro 47
Results at Lind 52
Results at Nephi 55
Depth of seeding experiments 58
Results at Moro 58
Results at Lind 59
Spacing and furrow-seeding experiments 60
Results at Moro 60
Results at Lind 62
Results at Nephi 65
Summary 66

TECHNICAL BULLETIN No. 330.—ROTATION AND TILLAGE EXPERIMENTS AT THE LAWTON (OKLA.) FIELD STATION, 1917–30 (W. M. Osborn):

Introduction 1
Crops grown in the region 2
Description of the station 3
Climatic conditions 4
Rotation and tillage experiments 6
Results with corn 7
Results with kafir 10
Results with sorgo 15
Results with feterita 17
Results with milo 19
Results with corn, kafir, sorgo, and feterita under continuous cropping 19
Results with broomcorn 21
Results with cotton 21
Results with wheat 25
Results with oats 28
Results with barley 29
Comparative yields of wheat, oats, and barley 29
Results with cowpeas 30
Results with alfalfa 32
Results with sweetclover 33
Results with peanuts 33
Summary and conclusions 33

TECHNICAL BULLETIN No. 331.—PHAEOGENES NIGRIDENS WESMAEL, AN IMPORTANT ICHNEUMONID PARASITE OF THE PUPA OF THE EUROPEAN CORN BORER (H. D. Smith):

Introduction 1
Geographical distribution 2
History 2
Systematic position 3
Host relations 3
Method of investigation 4
Explanation of symbols used in the illustrations 5
Description 6
Adult 6
Egg 8

TECHNICAL BULLETIN No. 331—Continued.
Description—Continued. Page
Larva 8
Prepupa 21
Pupa 21
Biology 21
Emergence 21
Behavior on the first day after emergence 22
Light reaction 22
Food 22
Mating 23
Oögenesis 23
Oviposition 24
Incubation 25
Larval development 26
Prepupal development 28
Pupation 29
Effect of parasite on host 29
Length of life of adult 30
Hibernation 30
Ratio of sexes 31
Parthenogenesis 32
Seasonal history 32
Armorican zone (Tours, Angers) 33
Rhodanian zone (Jura) 33
Aquitanian zone (Southwestern France) 33
Mediterranean (south) zone (Hyères) 34
Padovian (Piedmont) zone (Turin) 34
Padovian (north) zone (Bergamo, Pavia, Mantova) 34
Padovian (south) zone (Piacenza, Ferrara, Sermide) 35
Venetian (low) zone (Padua) 36
Venetian (high) zone (Treviso) 36
Plavisian zone (Udine) 36
Hungarian zone 36
Hyperparasites 36
Phaeogenes nigridens as a controlling factor of *Pyrausta nubilalis* 36
Limiting factors in effectiveness of *Phaeogenes nigridens* 38
Collection and shipment of the parasite 39
Summary 42
Literature cited 44

TECHNICAL BULLETIN No. 332.—THE BEARING STRENGTH OF WOOD UNDER BOLTS (George W. Trayer):
Introduction 1
Limits of the investigation 2
Character of the tests 2
Bearing parallel to the grain 2
Bearing perpendicular to the grain 3
General procedure 3
Proportional limit of a bolted joint 5
Bolt-bearing strength of wood parallel to the grain 6
Discussion of test results 6
Safe working stresses parallel to the grain for common bolts 12
Summarized procedure for calculating safe loads parallel to the grain 18
Effect of repeated loads 18
Safe working stresses parallel to the grain for bolts of high strength 20
Bolt-bearing strength of wood perpendicular to the grain 21
Discussion of test results 21
Safe working stresses perpendicular to the grain for common bolts 25
Summarized procedure for calculating safe loads perpendicular to the grain 29
Safe working stresses perpendicular to the grain for bolts of high strength 30
Bolt-bearing strength of wood at any angle with the grain 31
Formula for calculation 31

TECHNICAL BULLETIN No. 332—Continued. Page
Details of design 32
1-end loading compared with 2-end loading 32
Combined action of several bolts in a joint 32
Choice of bolt diameter 33
Placement of bolts in a joint 33
Centering and boring the bolt holes 36
Cross bolts 37
Condition of lumber 37
Appendix 38
Method of fitting stress curves to the data 38

TECHNICAL BULLETIN No. 333.—FOOD SUPPLY AND PELLAGRA INCIDENCE IN 73 SOUTH CAROLINA FARM FAMILIES (Hazel K. Stiebeling and Hazel E. Munsell):
Introduction 1
Scope and method of study 2
Classification of families 3
Physical examinations 5
Food-consumption data collected 6
Methods of evaluating food-consumption data 7
Method of calculating the money value of the food used 10
Food supply of unaided families 10
Complete dietary records over short periods 11
Use of specified food materials in relation to the incidence of pellagra 14
Food selection in relation to money value of diets 16
Use of supplementary foods in relation to incidence of pellagra among aided families 18
Dry skim milk 18
Evaporated milk 19
Wheat germ 19
Cured lean pork 19
Canned tomatoes 19
Pure dried yeast 20
General observations 20
Incidence of pellagra in relation to sex and age 21
Suggestions for improving diets 21
Summary and conclusions 22
Appendix 23
Literature cited 34

TECHNICAL BULLETIN No. 334.—THE EFFECT OF INORGANIC ACIDS ON THE PHYSICAL PROPERTIES OF WATERLEAF RAG BOND PAPER (T. D. Jarrell, J. M. Hankins, and F. P. Veitch):
Introduction 1
Review of the literature 1
Experimental procedure 3
Results 5
Discussion of results 9
Untreated control 10
Effect of aluminum sulphate 11
Effect of sulphuric acid 12
Effect of hydrochloric acid 13
Conclusions and summary 14
Literature cited 15

TECHNICAL BULLETIN No. 335.—FERTILIZERS FOR SWEETPOTATOES BASED ON INVESTIGATIONS IN NORTH CAROLINA (J. J. Skinner, C. B. Williams, and H. B. Mann):
Introduction 1
Fertilizer ratio experiments 3
Plan of experiments 3
Soil types and results obtained 4
Different quantities of fertilizers 18
Nitrogen sources 20
Potash sources 23

TECHNICAL BULLETIN No. 335—Continued. Page
Fertilizer placement and time of application 25
Concentrated fertilizers 34
Summary 43
Literature cited 45

TECHNICAL BULLETIN No. 336.—ATTRACTANTS FOR THE FLYING GIPSY MOTHS AS AN AID IN LOCATING NEW INFESTATIONS (C. W. Collins and S. F. Potts):
Introduction 1
Types of cages and marking and liberation of males 3
Living female moths as source of attraction 5
Flight of males and proportion finding females 6
Distances males fly in seeking females 8
Distances males fly in confinement 9
Tests of trapping males on a large scale 10
Recovery experiments with extracts in Maine 12
Chemical studies of the attracting substance 14
Test for acid 17
Hydrolysis with acid 18
Test for base 18
Test for unsaturated compounds 18
Test for aldehydes 18
Volatility tests 18
Thermal test 19
Anatomical studies 20
Tests of extracts 23
Experiments from 1920 to 1927 23
Experiments in 1928 28
Experiments in 1929 31
Results with various absorbent materials 32
Test of age of females 33
Results of other tests at Saugus, Mass 35
Obtaining female abdominal tip material 36
Use of extracts to locate new infestations in New England 39
Use of extracts in New Jersey 41
Summary 43

TECHNICAL BULLETIN No. 337.—THE PORTABLE BAND SAWMILL AND SELECTIVE LOGGING IN THE LOBLOLLY PINE FORESTS OF NORTH CAROLINA (R. D. Garver and J. B. Cuno):
Introduction 1
Purpose 2
Area studied 2
The portable band sawmill 6
Logging and milling methods 7
How the study was made 8
Cost of producing lumber from logs and trees of different sizes 8
Logging costs for loblolly pine trees 9
Overrun for loblolly pine and hardwood logs and trees 10
Total production cost for loblolly pine logs and trees of different diameters 11
Lumber prices 14
Grades and value of lumber 14
Production costs and lumber values compared 17
Returns from different diameter cutting limits 21
Application of results to utilization and forest practice in North Carolina 23
Log grades 26
Volume and value of individual loblolly pine trees 28
Conclusions 28

TECHNICAL BULLETIN No. 338.—RELATION OF LEAF AREA AND POSITION TO QUALITY OF FRUIT AND TO BODY DIFFERENTIATION IN APPLES (M. H. Haller and J. R. Magness):
Introduction 1
Material and methods 2

TECHNICAL BULLETIN No. 338—Continued. Page
Relation of leaf area to growth and composition of apples 4
Increase in size of fruit 5
Chemical composition 10
Dessert quality 12
Firmness 13
Color development 13
Relation of distance and direction of fruit from leaves to size and composition of apples 15
Relation of leaf distance to growth of fruit 15
Relation of direction of apples from leaves to growth of fruit 19
Relation between number of seeds per apple and size of fruit 20
Relation between leaf distance and chemical composition of fruit 20
Relation of leaf area per apple to bud differentiation 22
Review of previous work 22
Results of present investigations 25
Discussion 29
Summary 32
Literature cited 33

TECHNICAL BULLETIN No. 339.—SOME RESULTS OF INBREEDING GRADE GUERNSEY AND GRADE HOLSTEIN-FRIESIAN CATTLE (T. E. Woodward and R. R. Graves):
Purpose, plan, and progress of the investigation 1
Effects of inbreeding grade Guernseys 3
Birth weight of calves 4
Normality of calves at birth 4
Mature weight of cows 5
Production of milk and butterfat 6
Color markings 8
Effects of inbreeding grade Holsteins 8
Breeding of bulls used 8
Breeding of foundation cows 9
Services required for conception 9
Gestation and normality of calves 9
Birth weight of calves 10
Mortality of calves 20
Rate of growth of calves 20
Mature weight of cows 22
The vigor of cows 23
Production of milk and butterfat 23
Color markings 30
Summary 30

TECHNICAL BULLETIN No. 340.—DISTINCTIVE EFFECTS OF THE DEFICIENCY OF CERTAIN ESSENTIAL ELEMENTS ON THE GROWTH OF TOBACCO PLANTS IN SOLUTION CULTURES (J. E. McMurtrey, Jr.):
Introduction 1
Review of literature 2
Methods of experimentation 4
Experimental data 8
Interpretation and discussion of results 15
Growth in control solutions 16
Nitrogen deficiency 16
Phosphorus deficiency 20
Potassium deficiency 22
Magnesium deficiency 23
Calcium deficiency 25
Boron deficiency 27
Sulphur deficiency 29
Iron deficiency 31
Manganese deficiency 32
Chlorine deficiency 34
Comparison of deficiency effects 34
General considerations 40
Summary 40
Literature cited 42

TECHNICAL BULLETIN No. 341.—EFFECTS OF CERTAIN ENVIRONMENTAL FACTORS ON STRIPE DISEASE OF BARLEY AND THE CONTROL OF THE DISEASE BY SEED TREATMENT (R. W. Leukel, J. G. Dickson, and A. G. Johnson): Page

Introduction 1
Nature of the disease 2
Time and manner of inoculation 4
Location of the fungus in the seed 4
Longevity of conidia and seed-borne mycelium 5
Viability of seed from diseased plants 6
Secondary infection 6
Effect of environmental conditions 7
Soil fertility 7
Soil temperature and moisture 7
Control of stripe disease by seed treatment 14
Experiments in 1926 16
Experiments in 1927 17
Experiments in 1928 25
Experiments in 1929 28
Experiments in 1930 31
Discussion 34
Summary 36
Literature cited 37

TECHNICAL BULLETIN No. 342.—CAUSES OF BRASHNESS IN WOOD (Arthur Koehler):

Introduction 1
Brashness and toughness 1
Properties of brash wood 4
Accidental factors affecting type of failure and toughness of wood 8
Causes of brashness investigated 10
Species differences 10
Environmental factors 10
Width of growth rings 10
Percentage of summer wood 12
Sapwood as compared with heartwood 13
Cellular structure of wood low in density for its species 14
Cellular structure of wood of medium and of high density for its species 18
Existing compression failures 27
Cross grain 31
Height in tree 31
Distance and direction from center of tree 32
Ratio of tensile to compressive strength 32
High temperature 33
Chemical composition 35
Decay 36
Summary 37
Literature cited 38

TECHNICAL BULLETIN No. 343.—SPECIFIC GRAVITY AND RELATED PROPERTIES OF SOFTWOOD LUMBER (Edward C. Peck):

Introduction 1
Factors that influence the weight of wood 2
Wood substance 2
Spring wood and summer wood 2
Moisture 2
Extractives 4
Compression wood 4
Decay 4
Growth conditions 4
Position in the bole 5
Geographical location 5
Method of experimentation 5
Scope 5
Collection of specimens 9
Specific-gravity determinations 9

TECHNICAL BULLETIN No. 343—Continued. Page
Discussion of results 9
Specific-gravity data 9
Species and regional comparisons 10
Mill comparisons 14
Comparison of average specific gravity of different qualities of lumber of the same species 15
Comparison of present data with previously published data 16
Relation between specific gravity and various properties 17
Mechanical properties 17
Drying rate 18
Equilibrium moisture content 19
Shrinkage 19
Woodworking properties 19
Painting properties 20
Gluing properties 20
Raised grain 20
Shipping weights 20
Treating properties 22
Fuel value 22
Heat conductivity 22
Pulp yield 22
Summary 22
Literature cited 23

TECHNICAL BULLETIN No. 344.—PETROGRAPHIC METHODS FOR SOIL LABORATORIES (W. H. Fry):
Introduction 1
Crystal form 4
Fundamental properties of light 6
Polarized light 9
Double refraction 10
Becke lines 13
Interference of light 14
The petrographic microscope and accessories 16
Mechanical parts 16
Optical system 18
Calibration and measurements 25
Optical methods 33
Immersion media 33
Determination of refractive index by Becke line 34
Determination of two indices of refraction 36
Determination of three indices of refraction 37
Interference figures 39
Optical character 45
Optic-axial angle 48
Dispersion of optic axes 50
Measurement of double refraction (birefringence) 53
Extinction angles 58
Sign of elongation 61
Color of crystals 61
Pleochroism 62
Orientation 63
Application of methods 63
Pure substances 63
Identification of minerals in soils 64
Percentage estimation of constituents in a mixture (mechanical analysis) 71
Differentiation of soil colloids from soil crystalline material 76
Soil organic matter and residue of organisms 78
Shape of particles 79
Residues from the evaporation of soil solutions 81
Vertical illumination 82
Particle surfaces 82
Soil structure 83

TECHNICAL BULLETIN No. 344—Continued.
Application of methods—Continued. Page
Ultramicroscopes 84
Fertilizer materials 85
Miscellaneous materials 86
Inspection of samples for purity 86
Phase-rule problems 87
Literature cited 95

TECHNICAL BULLETIN No. 345.—BIOLOGY AND MORPHOLOGY OF THE SPINDLE WORM, OR ELDER BORER (J. C. Silver):
Introduction 1
Character and extent of injury to corn 2
Historical 2
Distribution 3
Food plants 4
Character and extent of injury to elder 4
Description of *Achatodes zeae* 6
The egg 6
The larva 6
The pupa 8
The adult 8
Experimental methods 10
Life history and habits 10
The moth 10
The larva 11
Pupal cells 14
Prepupa 14
Pupa 14
Longevity of adults 14
Seasonal development 14
Artificial dissemination 15
Natural dissemination 15
Natural control 15
Parasites 15
Birds and rodents 18
Artificial control 18
Summary 18
Literature cited 18

TECHNICAL BULLETIN No. 346.—THE EFFECT OF CONCENTRATION ON THE TOXICITY OF CHEMICALS TO LIVING ORGANISMS (Ernest Bateman):
Introduction 1
Effect of the concentration of chemicals on the retardation of the growth of the wood-destroying fungus *Fomes annosus* 2
Method of conducting the tests 2
Petri-dish method 2
Flask method of testing toxicity 7
Calculation of experimental data 10
Mathematical discussion 17
Experimental results 19
Inorganic compounds 19
Organic chemicals 20
Discussion of experimental results 25
Conclusions from experimental work 26
Work of other investigators 26
Application of the analysis to data on bean aphis 27
Application of the analysis to data on the bacteria *Staphyloccus pyogenes aureus* and *Bacillus paratyphosus* and on anthrax spores 30
Application of the analysis to data on green plants 32
Extension of the analysis to stimulation 33
Application of the hypothesis to *Bacterium coli* 37
Application of the hypothesis to the sprouting of wheat 37
Application of the hypothesis to growing peas 39

TECHNICAL BULLETIN No. 346—Continued.
Extension of the analysis to stimulation—Continued. Page
Application of the hypothesis to fungi 41
Application of the hypothesis to hydrogen ion 42
Discussion of the hypothesis 46
Application of the hypothesis to antagonism 48
Summary and conclusions 52
Literature cited 52

TECHNICAL BULLETIN No. 347.—AN ECONOMIC STUDY OF BROOMCORN PRODUCTION (R. S. Washburn and J. H. Martin):
Introduction 1
Trend of broomcorn production 2
Origin and introduction of broomcorn 2
Shifts of broomcorn growing 3
Quantity of broomcorn produced 4
Price and supply of broomcorn 7
Early prices 7
Recent prices 8
Competition of other products 11
Export demand for American broomcorn 12
Relation of supply of broomcorn to price received 14
Acreage of broomcorn needed to produce an adequate supply 17
Cost of production and returns from broomcorn and competing cash crops 17
Illinois 18
Usual field practice in growing broomcorn and the major competing cash crop 18
Practices that should increase profits 20
Cost of production 21
Annual broomcorn yields 25
Variation in labor and power requirements 25
Kansas 27
Usual field practice in growing broomcorn and the major competing cash crop 27
Practices that should increase profits 29
Cost of production 29
Oklahoma 32
Usual field practice in growing broomcorn and the major competing cash crop 32
Practices that should increase profits 33
Cost of production 33
Choice of competing cash crops 36
Net returns per acre from broomcorn and competing cash crops 36
Summary 40
Literature cited 41

TECHNICAL BULLETIN No. 348.—USE OF THE EXPONENTIAL YIELD CURVE IN FERTILIZER EXPERIMENTS (W. J. Spillman):
Introduction 1
Yield curve for a single variable growth factor 5
Determination of the constants of the exponential curve 5
Graphic method 5
Logarithmic method 7
New method 9
Demonstration using experimental results with three variable factors 16
Ammonia series 19
Phosphoric acid series 20
Potash series 21
All three variables taken together 21
Final calculated yields 25
Yield of check plots 25
Optimum fertilizer formulas 27
Optimum quantity of fertilizer 32
Optimum acreage to which to apply fertilizer costing a fixed amount 36

TECHNICAL BULLETIN No. 348—Continued. Page
Absorption, or occlusion, of plant food 41
Form of the yield curve 46
Derivation of the exponential yield curve 51
One-variable form 51
General form 54
Plan for obtaining data 55
Series of plots 56
Use of check plots 57
Other factors to be considered 58
Summary 59
Appendix 59
Tables of values of R^x and $1-R^x$ 59
Literature cited 66

TECHNICAL BULLETIN No. 349.—ANALYSIS OF THE ADVANCED REGISTRY RECORDS OF 611 DAUGHTERS OF 51 AYRSHIRE SIRES (M. H. Fohrman and R. R. Graves):
Introduction 1
Source of data and materials used 2
Analysis of records of milk production 2
Comparative statistics of dams and daughters 2
Groups of sires with daughters having highest average production and highest average increase over dams 7
Individual sires in relation to milk records of their daughters 8
Full-sister groups of daughters 22
Significance of correlation coefficients of milk production of dams and daughters 28
Influence of milk record of sire's dam 29
Half sisters of the sires 31
Methods of mating 35
Combinations of sires in relation to their influences on milk production 35
Analysis of records of butterfat test 36
Groups of sires with daughters having highest average butterfat test and highest average increase in test over dams 39
Individual sires in relation to butterfat test of their daughters 41
Significance of correlation coefficients and coefficients of variability of butterfat test of dams and daughters 50
Full-sister groups of daughters 52
Influence of butterfat test of sire's dam 53
Sires that increased both quantity of milk and percentage of butterfat 55
Independent inheritance of quantity of milk and percentage of butterfat 57
Summary and conclusions 57

TECHNICAL BULLETIN No. 350.—EFFECT OF LEAD ARSENATE INSECTICIDES ON ORANGE TREES IN FLORIDA (R. L. Miller, Ione P. Bassett, and W. W. Yothers):
Introduction 1
Previous work 2
Method of investigation 4
Arsenical determinations 5
Respiration 5
Catalase activity 5
Fruit analysis 5
Kind of citrus trees used 5
Effect of lead arsenate on citrus trees when applied to the soil 5
Method of analysis 6
Penetration into the soil 6
Effect of foliage and fruit 6
Effect on undergrowth 7
Loss of arsenic from the soil 7
Application of lead arsenate to tree and fruit 7
Time the insecticide remains on the tree after spraying 7
Arsenical content of wood, bark, blossoms, and small fruit of sprayed trees 8

TECHNICAL BULLETIN No. 350—Continued.
Application of lead arsenate to tree and fruit—Continued. Page
Effect of arsenicals on respiration of orange leaves 9
Effect of arsenicals on catalase activity of orange leaves 11
Relation between leaf processes and condition of the fruit 12
Effect of arsenicals on oranges when leaves and fruit were sprayed 14
Effect of arsenic not systemic 18
Relation between time arsenical spray remained on leaves and its effect on citrus fruit 18
Summary 19
Literature cited 20

TECHNICAL BULLETIN No. 350 FEBRUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D C

EFFECT OF LEAD ARSENATE INSECTICIDES ON ORANGE TREES IN FLORIDA

By R. L. MILLER, *Associate Entomologist*, IONE P. BASSETT, *Senior Scientific Aid*, and W. W. YOTHERS, *Entomologist, Division of Fruit and Shade Tree Insects, Bureau of Entomology*

CONTENTS

	Page
Introduction	1
Previous work	2
Method of investigation	4
Arsenical determinations	5
Respiration	5
Catalase activity	5
Fruit analysis	5
Kind of citrus trees used	5
Effect of lead arsenate on citrus trees when applied to the soil	5
Method of analysis	6
Penetration into the soil	6
Effect on foliage and fruit	6
Effect on undergrowth	7
Loss of arsenic from the soil	7
Application of lead arsenate to tree and fruit	7
Time the insecticide remains on the tree after spraying	7
Application of lead arsenate to tree and fruit—Continued	
Arsenical content of wood, bark, blossoms, and small fruit of sprayed trees	8
Effect of arsenicals on respiration of orange leaves	9
Effect of arsenicals on catalase activity of orange leaves	11
Relation between leaf processes and condition of the fruit	12
Effect of arsenicals on oranges when leaves and fruit were sprayed	14
Effect of arsenic not systemic	18
Relation between time arsenical spray remained on leaves and its effect on citrus fruit	18
Summary	19
Literature cited	20

INTRODUCTION

One of the important methods used in the successful campaign to eradicate the Mediterranean fruit fly (*Ceratitis capitata* Wied.) from Florida was the application of a poison spray on which the adult flies fed. The most effective bait spray available in this emergency contained lead arsenate as the poison. Although it had been known for many years that arsenic hastened the maturity of citrus fruit by reducing the acid content and that its use had, in some instances, rendered the fruit unpalatable, the menace of this insect pest to the citrus industry of Florida and to fruit production elsewhere in the United States was so great that the authorization for the use of this poison was fully justified, and its use was approved by responsible State officials.

During the eradication campaign voluminous notes were accumulated as to the effect of the bait sprays on citrus trees and fruit. These notes were of a general nature, and the observations recorded were more or less conflicting. It seemed necessary, therefore, to conduct some carefully planned experiments to secure accurate information on the effect of arsenic on citrus trees. This bulletin reports the results of fundamental investigations carried on under funds providing for necessary research to eradicate this major pest from Florida.

155741—33——1

PREVIOUS WORK

Soon after arsenic was first used on citrus in Florida—in 1893, by Lyman Phelps—it was found that the fruit on arsenic-sprayed trees matured more quickly than other fruit (*5, p. 81*).[1] Since that time arsenical materials have been used considerably, sometimes to control insects but more often to hasten the legal maturity of the fruit. Certain insecticides that have been sold in Florida have been found to contain arsenic in considerable quantities. In one case, in 1915, as much as 2.93 per cent of arsenic trioxide (As_2O_3) was found in a commonly known material.[2]

In 1921 Gray and Ryan (*9*) published an account of some arsenical spraying in California. They found that when acid lead arsenate was used the acidity of oranges was reduced 50 per cent or more from the normal but that the sugars were not significantly changed. When basic, or neutral, lead arsenate was used there was little or no change in acidity. These workers believed the acid reduction to be due to the soluble arsenic liberated on the foliage. They stated that the effect on the tree probably was systemic, for all the fruits examined from the sprayed trees were of reduced acidity.

In 1925 Juritz (*11*) discussed the use of arsenic on citrus trees in South Africa. The treatment of the trees and the effect on the acid and sugar of the fruit are shown in Table 1, which is taken from his report.

TABLE 1.—*Analysis of sprayed and unsprayed oranges made by C. F. Juritz in South Africa, 1925*

Insecticide used per tree	Analyses of fruit	
	Acid	Sugar
	Per cent	*Per cent*
Lead arsenate mixture, 53 ounces	0.18	1.12
Lead arsenate mixture, 26½ ounces	.49	3.65
Check, unsprayed	1.12	4.14

Juritz stated that the effect remained more than a year and that the whole tree was systemically affected if only one-half was sprayed. He was the first worker to report that the soluble solids of the juice were seriously reduced.

In 1925 the State of Florida passed legislation restricting the sale of fruit that did not pass certain maturity tests of acid and soluble-solids requirements (*6*). When this was done and certain growers realized that the legal maturity of fruits could be hastened by arsenical spraying, many instances were found where the legal maturity was speeded up by spraying or dusting.

In 1926 Grossenbacher (*1*) suggested that there be some definite requirement regarding the ratio of solids to acid for a standard of legal maturity (i. e., a maximum as well as a minimum value for the ratio), thereby disqualifying arsenical-sprayed fruit. In 1927 the Florida Legislature passed a law forbidding the use of arsenic on citrus trees, but in 1929 amended it (*8*) to permit the use of arsenic when necessary in eradication measures such as those directed against the Mediter-

[1] Italic numbers in parentheses refer to Literature Cited, p. 20.
[2] Miscellaneous analyses 22611, made by C. H. Walker of the Bureau of Chemistry and Soils, U. S. Department of Agriculture.

ranean fruit fly, and again legislated against shipment of immature fruit (*7*).

Work done by Yothers and others in Florida in 1926 (*17*) established that only the part of the tree sprayed was affected. Examinations of sprayed trees showed that the fruit in the tops of the trees, which could not be reached by the spray, was normal, whereas that on the lower branches was considerably affected. This is shown in Table 2, which is condensed from a table in the article cited.

TABLE 2.—*Effect of lead arsenate on total soluble solids and ratio of acid to solids in oranges*

[Analyses of Nov. 10, 1926]

Source of fruit analyzed	Sugar	Acid	Ratio of acid to sugar
	Per cent	*Per cent*	
Top of tree	9.75	1.26	1 to 7.74
Lower limbs	9.00	.53	1 to 17.00
Top of tree	9.10	1.20	1 to 7.60
Lower limbs	8.85	.48	1 to 18.44

TABLE 3.—*Effect on oranges of arsenical applied as a dust*

[Analyses of Nov. 3, 1926]

Source of sample	Sugar	Acid	Ratio of acid to sugar
	Per cent	*Per cent*	
Dusted trees	9.70	0.14	1 to 69.30
Check trees	9.30	1.11	1 to 8.38

Trees that were dusted with 90 per cent sulphur and 10 per cent lime and lead arsenate were affected just as were those that had been sprayed, as shown in Table 3, which is from another table in the same article by Yothers.

Yothers reported that mature-picked fruit can not be changed by immersion in a lead arsenate mixture.

In 1927 Hawkins and Barger (*10*) corroborated the results of previous workers in the use of arsenic on citrus and advised against its general application for the purpose of hastening fruit maturity.

In 1927 Copeman (*3*), in South Africa, investigated the use of arsenical and other materials on citrus and found that arsenic reduced the acid in the fruit but that there was no significant change in the sugar content. He concluded that the effect was systemic and that the fruit was affected through the leaves. The quantity of arsenic used per tree by Copeman was apparently less than that used by Juritz.

Takahashi, working in Japan, published a paper in 1928 (*16*) in which he reviewed most of the previous work on arsenic. He corroborated the findings of other workers as to reduction of acid and increase of sugar in navel oranges on arsenical-sprayed trees, as shown in Table 4, which is taken from the article cited.

TABLE 4.—*Effect of lead arsenate in spray on navel oranges as determined by Ikuro Takahashi in Japan in 1928*

Treatment of plots	Average weight of fruit	Fruits	Pulp	Percentage of juice to pulp	Specific gravity of juice	Principal components of juice			Ratio of sugar to acid
						Citric acid	Reducing sugar	Total sugar	
Lead orthoarsenate, 2 pounds; lime sulphur (0.8 per cent), 50 gallons	*Grams* 222.1	*Number* 5	*Per cent* 76.73	64.55	1.050	*Per cent* 0.4533	*Per cent* 6.8646	*Per cent* 8.0128	17.67
Check	216.1	5	76.18	66.53	1.048	.9769	4.7250	7.5630	7.74

Takahashi found that the effect persisted for more than one season and stated that small fruits were more affected than large fruits. No attempt was made to explain how arsenic affected citrus trees, although the opinion was expressed that it was through the root system.

In 1931 Copeman (*4*) published a very comprehensive study of the effect of arsenic on the ripening of fruit, in which he confirmed, with additional evidence, the points mentioned in his previous paper.

In 1929 Singleton (*15*), in Florida, stated that lead arsenate used in the proportion of one-half pound to 200 gallons had a very desirable effect on citrus fruit, but that when used at greater strengths it was quite unsatisfactory.

Work done in 1929 by the senior author and McBride, which was reported in part in 1931 (*13*), showed that when the fruit itself or the leaves of the branches immediately surrounding the fruit were sprayed the fruit was affected. Dipping the small, green fruit on an unsprayed tree in lead arsenate suspension affected it just as would the spraying of the foliage, and when the fruit was protected by a paper bag and the leaves around it sprayed the fruit was affected.

In 1932 Nelson and Mottern (*14*) reported the results of the analysis of oranges, sent to them by the Orlando laboratory, which had been sprayed with lead-arsenate bait spray. Their analyses showed that these were very low in acid and also low in sucrose. An important point, however, is the fact that in oranges heavily sprayed with arsenic the vitamin C content was reduced considerably. These writers also reported that the arsenic content of the edible portion of the orange was not changed by spraying the tree with heavy doses of lead arsenate.

METHOD OF INVESTIGATION

Work on this problem was undertaken with the idea of determining how arsenical insecticides affect trees and fruit. Other workers have pointed out clearly that arsenic does affect citrus fruit through the leaves or trees, but have told practically nothing about the extent of effect from various quantities.

In order to determine whether or not arsenic may produce the effect through the soil instead of the leaves, large quantities of lead arsenate were applied to the soil under orange and grapefruit trees, and analyses of the soil, fruit, and foliage were made at intervals for two and one half years afterwards.

In all the spraying work only half of a tree was sprayed, and the remaining half was used as a check. The unsprayed portions of these trees were compared with the adjoining trees that had not been

sprayed, and no difference could be detected other than small differences attributed to the normal variabliity of trees. The unsprayed half of a tree was always used for a check on the sprayed half, and in this way individual tree differences were eliminated.

ARSENICAL DETERMINATIONS

Orange trees were sprayed with various quantities of acid lead arsenate, and at intervals of one month quantitative determinations were made of the water-soluble and insoluble arsenic remaining on the leaves.

RESPIRATION

Twigs from the same group from which the arsenical determinations were made were placed in respiration chambers and the quantity of liberated carbon dioxide measured. After this the relation between the arsenic present on the leaves and the quantity of carbon dioxide liberated was worked out.

CATALASE ACTIVITY

Other leaves from the same group were used for determining the quantity of catalase present in leaves on which the various quantities of arsenic were found.

FRUIT ANALYSIS

Fruit samples were taken for analysis from the trees that had been sprayed with arsenical insecticides, and determinations were made of the arsenic present, as well as of the relation between this chemical and the respiration and catalase of the leaves. When the fruit was quite small, approximately 25 to 30 mm in diameter, the hydrogen-ion concentration was measured electrically. As soon as enough juice was available the percentage of soluble solids was determined by a Brix hydrometer and the acid by titration with the standard alkali.

KIND OF CITRUS TREES USED

The work reported in this bulletin, except where otherwise stated, was carried on with orange trees. The principles involved in the effect of arsenic on grapefruit, tangerines, and other citrus fruits are probably the same as those involved in the effect on oranges, but the quantities of arsenic required to produce these effects may differ.

EFFECT OF LEAD ARSENATE ON CITRUS TREES WHEN APPLIED TO THE SOIL

There has been much theorizing as to the effect of the drip of arsenical insecticides on the soil beneath citrus trees. The writers were unable to find any published information on this point, although unpublished notes of work done in 1926 by W. W. Yothers, F. A. Wolf, and O. C. McBride reported the results of applications of arsenic to the soil under citrus trees. Paris green, white arsenic, and lead arsenate were used in quantities up to 1½ pounds per tree without any effect on fruit maturity as shown by either taste or chemical analyses. In the present work the quantity of arsenic applied to the soil was much greater than would result from the dripping of arsenical sprays over more than 250 years.

A seedling orange and a grapefruit tree more than 30 years old were chosen for the experiment. The treated and check trees were close to each other and on the same type of soil, which was Norfolk sand, well drained and having the average amount of humus.

The soil was sprayed at intervals of from one to two weeks with a hand-operated pressure apparatus fitted with a rod and nozzle. Sixty applications of one-half pound of lead arsenate (30 pounds in all) in 7½ gallons of water were made beneath the grapefruit tree, and 14 applications (7 pounds in all) beneath the orange tree.

METHOD OF ANALYSIS

To obtain the arsenic from the soil for analysis, the distillation method (*2, p. 35*) was used. Fifty grams of soil was found to be the most satisfactory quantity for the test. After the solution had been obtained from the distillation, the quantity of arsenic in the solution was determined by the modified Gutzeit method. The pH value of each sample was determined by the Welch hydrogen-ion-concentration apparatus.

PENETRATION INTO THE SOIL

The first analysis was made just after the 60 applications to the grapefruit tree and the 14 applications to the orange tree had been completed. The results are given in Table 5.

TABLE 5.—*Effect of arsenic in the soil on the fruit of grapefruit and orange trees, Orlando, Fla., 1931*

Variety	Parts of arsenic trioxide per million of soil		pH of soil	Fruit analyses		
	1 to 2 inches depth	8 to 10 inches depth		Acid	Solids	Ratio of solids to acid
				Per cent	*Per cent*	
Grapefruit	2,000	6.0	5.0	2.03	10.9	5.37
Check grapefruit	.04	.04	5.0	2.29	11.6	5.06
Orange	700	6.0	4.9	1.21	10.6	8.8
Check orange	.04	.04	5.0	1.14	9.2	8.1

After 30 pounds of acid lead arsenate ($PbHAsO_4$) had been applied to a slightly acid soil under the grapefruit tree, the first 2 inches of soil had arsenic present (as arsenic trioxide, As_2O_3) in the proportion of 2,000 parts per 1,000,000. During the 1½-year period over which this material had been applied there had been 115.15 inches of rainfall, and arsenic was found down as deep as 14 inches in the proportion of 3 parts of arsenic trioxide per 1,000,000 of soil. This makes it certain that the arsenic was well diffused among the roots, for almost all the roots of these citrus trees are found in the first foot of soil.

The orange tree under which 7 pounds of lead arsenate had been applied had proportional quantities, 700 parts per 1,000,000, in the upper 2 inches of the soil about its roots.

EFFECT ON FOLIAGE AND FRUIT

In the case of both the grapefruit and orange trees, the trees were absolutely normal, and only a trace of arsenic was found in the leaves. The flushes of growth appeared regularly, and the foliage was of nor-

mal size and color. The fruit was not affected, for by analyses the acid and solids were found to be but little different from those of the check trees. The color and size of the fruit were similar to those of the untreated trees near by.

EFFECT ON UNDERGROWTH

There were no differences in the growth of vegetation under the sprayed and unsprayed trees. With a few exceptions, there were the same plants, in the same state of growth, beneath both the sprayed and the unsprayed trees. Under the grapefruit tree where there were 2,000 parts of arsenic trioxide per 1,000,000 of soil, the following species were present: Spanish needle (*Bidens leucantha* L. Willd.), Mexican tea (*Chenopodium ambrosioides* D.), and ragweed (*Ambrosia bidentata* Michx.). Under the orange tree, where there were 700 parts of arsenic trioxide per 1,000,000 of soil, Spanish needle, Mexican tea, and crab grass (*Eleusine indica* Gaertn.) were growing normally. All of these plants grew under the check tree also. Because of the protection afforded by the lead arsenate there was little insect injury on the plants where the soil was treated.

LOSS OF ARSENIC FROM THE SOIL

Lead arsenate, when applied to the soil as in the foregoing experiments, is not readily leached out by the normal rainfall of Florida. A year after the previous analysis a second one was made of the soil beneath the grapefruit tree, and 1,800 parts of arsenic trioxide per 1,000,000 in the 1 to 2 inch range were found, and 5 parts at the 8 to 10 inch depth. Even though this large quantity of arsenic was present around the roots of the tree for over a year, the tree was normal and set a good crop of fruit. The vegetation beneath the tree was the same as during the previous year.

It is very improbable that any arsenical injury would ever result from the dripping of the spray material after an application of fruit-fly bait. When it is considered that 1 pint of a spray containing 8 pounds of lead arsenate to 200 gallons of water is sufficient for a tree, the 30 pounds used on the soil beneath the grapefruit tree would make enough spray material for 6,000 applications.

APPLICATION OF LEAD ARSENATE TO TREE AND FRUIT

TIME THE INSECTICIDE REMAINS ON THE TREE AFTER SPRAYING

The first and most important consideration in determining the effect of arsenical insecticides on orange leaves or foliage is an exact analysis to find the quantity of arsenic, soluble and insoluble in water, that remains on the leaves at various intervals after spraying.

Samples of leaves were taken from a representative part of the tree and were selected from such trees as would give a cross section of the entire treated or untreated plot. Ten grams of green weight was found to be the most satisfactory sample and these samples were always run in duplicate. The determination of arsenic was made by the official Gutzeit method (*2, p. 306*).

To determine the water-soluble arsenic, the leaves were kept for 10 minutes in 200 c c of distilled water, and this solution was then carefully filtered off and analyzed. The leaves and filter paper were then used to determine the water-insoluble arsenic.

To determine the total arsenic trioxide (As_2O_3), the arsenic was dissolved from the leaves with 2 per cent hydrochloric acid at room temperature (21° to 26° C., or 69.8° to 78.8° F.). The leaves, cut in half-inch strips, were kept in this solution for at least 10 minutes. At the end of this time they had usually turned yellow or brown. To check this method of removing arsenic from the leaves, many of the samples were afterwards digested and the remaining arsenic extracted by the distillation method (*2, p. 35*). The additional arsenic found was less than 1 per cent of the total arsenic of the sample.

The greatest quantity of soluble arsenic was present immediately after spraying, and during the first month two-thirds of this disappeared. After this there was only a gradual decrease. The rate of disappearance of arsenic from citrus trees is shown in Table 6 and in Figure 1.

TABLE 6.—*Milligrams of arsenic trioxide per 10 g*[1] *of fresh leaves at monthly intervals after one application of spray consisting of 8 pounds of lead arsenate to 200 gallons of water, Orlando, Fla., 1931*

Time after spraying, months	Arsenic trioxide (As_2O_3)		Cumulative rainfall	Time after spraying, months	Arsenic trioxide (As_2O_3)		Cumulative rainfall
	Water-soluble	Water-insoluble			Water-soluble	Water-insoluble	
	Mg	*Mg*	*Inches*		*Mg*	*Mg*	*Inches*
0	0.34	2.76		4	0.004	0.62	17.19
1	.08	1.39	3.02	5	.008	.33	20.91
2	.04	.82	5.09	6	.005	.19	22.21
3	.01	.53	12.04				

[1] g is the abbreviation for gram or grams.

The trees had been sprayed with 8 pounds of lead arsenate to 200 gallons of sirup-sugar mixture. During the six months there had been 22.21 inches of rain.

Analyses were made from time to time of leaves from trees that had been sprayed 1 year or 18 months previously, and arsenic was still found in quantities such as 0.001 mg per 10 g of leaves. There was very little difference in the solubility or rate of disappearance when either sirup and sugar or lime sulphur was added to the lead arsenate mixtures.

ARSENICAL CONTENT OF WOOD, BARK, BLOSSOMS, AND SMALL FRUIT OF SPRAYED TREES

In an effort to determine what happens to the arsenic that is sprayed on citrus trees, analyses of thoroughly acid-washed bark and wood from limbs 1 inch in diameter, as well as blossoms and small, green fruit one-fourth to three-eighths inch in diameter, were made.[3] In 201 out of 204 samples in which live bark and wood given 15 applications of 1 quart of fruit-fly bait spray were analyzed, the bark showed more arsenic than the wood. The arsenic in the bark ranged from 0 to 4.5 mg per kilogram of bark. In the wood, from 0 to 2.05 mg of arsenic was present per kilogram of wood. In the analyses of orange blossoms from similarly sprayed trees arsenic was found to be

[3] MCBRIDE, O. C., MARLOWE, R. H., and BASSETT, I. P. GUTZEIT DETERMINATIONS FOR ARSENIC IN CITRUS FRUIT JUICES, LEAVES, TWIGS, AND BLOSSOMS. Unpublished manuscript on file in Bureau of Entomology, U. S. Department of Agriculture.

present in quantities ranging from 0 to 6.9 mg of arsenic trioxide per kilogram of sample. In the small fruit the quantity of arsenic present ranged from a trace to 0.16 mg of arsenic trioxide per kilogram of sample.

In all the analyses of bark, wood, blossoms, and small fruit made above, the samples were taken from trees to which no arsenic had been applied for at least four months. This shows that in the case of the wood and the blossoms and small fruit which were produced the next season after the sprays were applied, the arsenic had been translocated from the sprayed parts.

EFFECT OF ARSENICALS ON RESPIRATION OF ORANGE LEAVES

Respiration, one of the most vital processes carried on by living plants, was studied to determine how it was affected by various

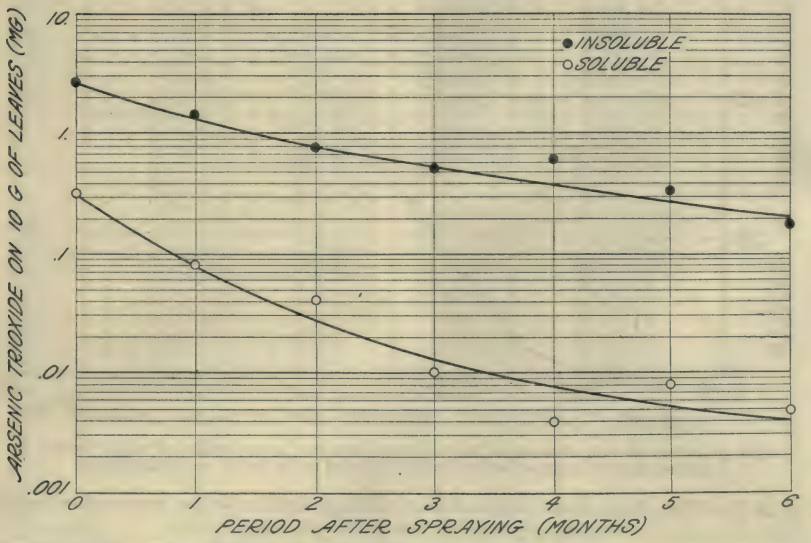


FIGURE 1.—Quantities of arsenic trioxide per 10 g of fresh leaves at monthly intervals after one spraying of 8 pounds of lead arsenate in 200 gallons of water. Semilogarithmic

quantities of arsenic. The fact that arsenic stimulated respiration in Elodea had been established by Lyon (*12*). In this case he submerged Elodea in an arsenical solution and found that respiration was stimulated up to 160 per cent of normal.

In the present work the rate of respiration was measured by determining the quantity of carbon dioxide liberated in a closed jar at a constant temperature, 25° C. (77° F.). The gas, carbon dioxide, was absorbed in sodium hydroxide solution (tenth normal) and titrated against hydrochloric acid (tenth normal) by the use of the double-indicator method.

When a test was to be made, twigs having from three to five leaves were cut under water, and the cut end was put in a vial of water. During the 2-day run the whole assembly was kept in a jar with the sodium hydroxide in the bottom. The sodium hydroxide was titrated once daily. The entire experiment was run in a dark room, and the

twigs were kept at a temperature that varied less than one-half degree during the time of the experiment. After each run was completed, the area of leaves used was determined by a planimeter, and the weight of carbon dioxide liberated per square inch per 24 hours was used in comparison. In all cases the determinations were made in triplicate and the mean of the three used. The results of these observations are shown in Table 7 and Figure 2.

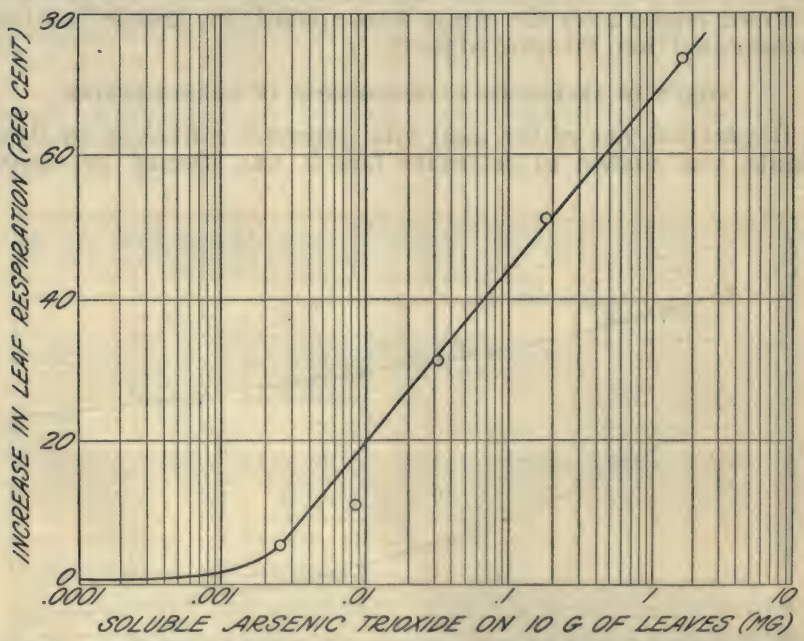


FIGURE 2.—Effect of lead arsenate in various quantities on the respiration of orange leaves, expressed in percentage of carbon dioxide liberated in the dark. Semilogarithmic

TABLE 7.—*The effect of lead arsenate in various quantities on the respiration (carbon dioxide liberated in the dark) of orange leaves*

Treatment	Determinations made	Average soluble arsenic trioxide per 10 g of green leaves	Carbon dioxide liberated per square inch per day	Increase in liberation of carbon dioxide
	Number	*Mg*	*Mg*	*Per cent*
Unsprayed, check	27	0	1.68	
Sprayed with dilute arsenical solution	3	.0026	1.78	6.0
	5	.0086	1.89	12.5
	20	.0306	2.23	32.7
Sprayed with concentrated arsenical solution	7	.1930	2.54	51.2
	2	1.75	2.91	72.0

As can readily be seen, water-soluble arsenic in very small quantities increases respiration. When only enough arsenic is present on orange leaves to stimulate respiration 5 to 10 per cent (less than 0.01 mg soluble arsenic trioxide on 10 g of green leaves) there is no injury; the leaves even become more glossy and take on a more intense shade of green. When the quantity is increased the stimulation is increased

in direct proportion, and when the stimulation goes from 50 to 75 per cent above normal the leaves become yellow, and when the quantity is increased beyond that point the leaves usually drop.

When compounds of arsenic of different solubility were used, as when lead arsenate was compared with some form of a soluble arsenic compound, such as sodium arsenate, it was found that the stimulation was in direct proportion to the quantity of soluble arsenic on the leaves.

It has been pointed out that arsenic remains on trees for long periods after the spraying has been done. It is here shown that when soluble arsenic is present on citrus leaves the respiration is stimulated. Other experiments extending over the entire growing season have shown that the respiration of arsenical-sprayed trees

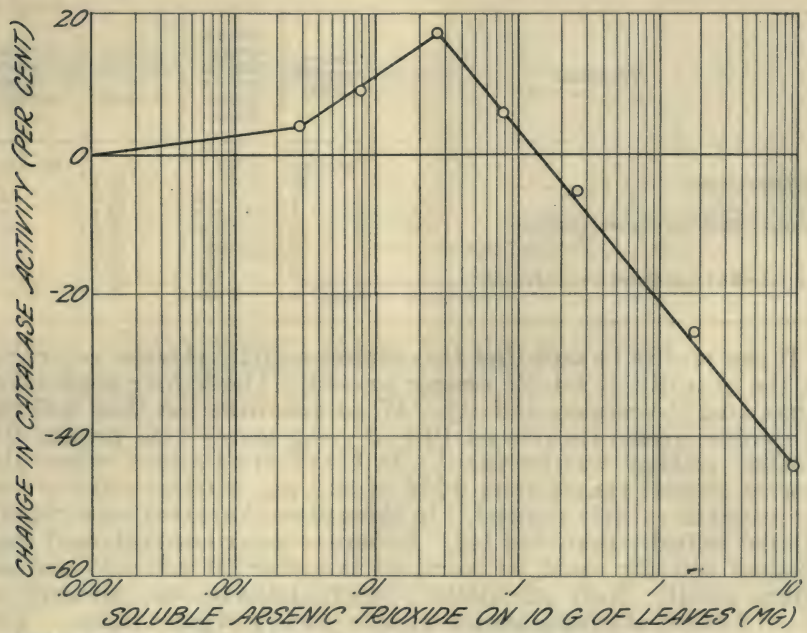


FIGURE 3.—Effect of lead arsenate in various quantities on the catalase activity of orange trees. Semilogarithmic

was constantly stimulated as long as lead arsenate was present on the leaves.

EFFECT OF ARSENICALS ON CATALASE ACTIVITY OF ORANGE LEAVES

One of the standards used recently as a measure of the state of growth or condition of plants is the quantity of catalase present. In general, other workers have found that leaves that are growing vigorously show a high catalase content as compared with those that are yellow or are growing poorly. Determinations were made both on a small scale from twigs sprayed by hand and from the trees that were given normal applications in the field.

The quantity of oxygen liberated from hydrogen peroxide by the catalase of the leaves was used as an index of the catalase activity. In making this determination five disks 1 cm^2 each were cut from

leaves washed in tap and distilled water and ground to a smooth paste with an equal quantity of calcium carbonate ($CaCO_3$) and a few drops of water. This was washed into a flask with 15 to 20 ml of distilled water and allowed to stand at 25° C. (77° F.) for one hour. Then it was connected to the apparatus where 20 c c of neutralized hydrogen peroxide (H_2O_2) was introduced and the quantity of oxygen evolved in five minute measured at one-half minute intervals. All the determinations were made in a water bath at 25° C.

The quantity of soluble arsenic on the leaves from which the disks were taken was determined by the Gutzeit method. The results of the experiment are shown in Table 8 and Figure 3.

TABLE 8.—*The effect of lead arsenate in various quantities on the catalase activity of orange leaves*

Treatment	Determinations made	Soluble arsenic trioxide per 10 g of fresh leaves	Oxygen liberated in 5 minutes	Increase or decrease in catalase activity
	Number	*Mg*	*Ml*	*Per cent*
Unsprayed, check	29	0	32.4	
Sprayed with dilute arsenical solutions	4	.0027	33.8	4.3
	4	.0075	35.4	9.3
	10	.028	38.0	17.3
	6	.081	34.3	5.9
Sprayed with concentrated arsenical solutions	10	.255	30.7	−5.2
	10	1.808	24.3	−25.0
	2	9.600	17.9	−44.8

It can readily be seen that the catalase activity changes according to the quantity of soluble arsenic present. The lighter application stimulated the catalase activity. When quantities less than 0.05 mg of soluble arsenic trioxide on 10 g of green leaves were present the catalase activity was increased. In heavy applications, where the arsenic trioxide ranged from 0.255 to 10.0 mg, catalase activity was decreased or entirely stopped. In these cases the leaves were usually injured so badly that they fell. Extensive experiments showed that catalase activity could be increased not over 10 per cent and no injury result. Such stimulation usually followed the presence of about 0.01 mg of soluble arsenic trioxide per 10 g of green leaves. The quantity that caused the most favorable stimulation of respiration caused the most favorable stimulation of catalase activity also.

RELATION BETWEEN LEAF PROCESSES AND CONDITION OF THE FRUIT

The relation between the respiration of orange leaves during the growing season and the percentage of acid in the mature fruit is very definite. The respiration was measured several times during the growing season, and the average increase or decrease over the check was recorded in terms of per cent. The acid was determined at maturity and considered as a per cent increase or decrease over the check. The check in each case was the unsprayed part of the same tree from which the respiration studies and fruit analyses had been made. This relation is shown in Table 9 and Figure 4.

FIGURE 4.—Relation between respiration of orange leaves during the growing season and the acid in the fruit at maturity

TABLE 9.—*The relation between the respiration of orange leaves during the growing season and the acid in fruit at maturity*

Treatment [1]	Increase over normal in respiration of leaves [2]	Decrease from normal in acid in fruit juice
	Per cent	*Per cent*
Check, no treatment	0	
Lead arsenate, 1 pound; water, 50 gallons	6.5	74.1
Do	14.3	73.4
Lead arsenate, 2 pounds; water, 50 gallons	34.6	75.1
Do	41.5	85.3

[1] 1 application June 4, 1931. [2] Average of 4 monthly analyses.

As can quite readily be seen, when the respiration is increased the acid in the fruit is reduced.

Besides the relation between the acid and respiration, there appears to be an agreement between the catalase activity of the orange leaves and the soluble-solids content of the fruit juice at maturity. Table 10 and Figure 5, indicating this relation, show a maximum increase in soluble solids of 1.5 per cent. Differences as small as this, however, should be the result of many determinations under various conditions before they can be considered significant.

TABLE 10.—*Relation between soluble solids of orange juice at maturity and the catalase activity of leaves during the growing season*

Treatment [1]	Increase in catalase activity [2]	Increase or decrease in soluble solids
	Per cent	*Per cent*
Check, no treatment	0	
Lead arsenate, 1 pound; water, 50 gallons	7.6	1.5
Lead arsenate, 2 pounds; water, 50 gallons	21.5	0
Do	28.5	—.5

[1] 1 application June 4, 1931. [2] Average of 4 monthly analyses.

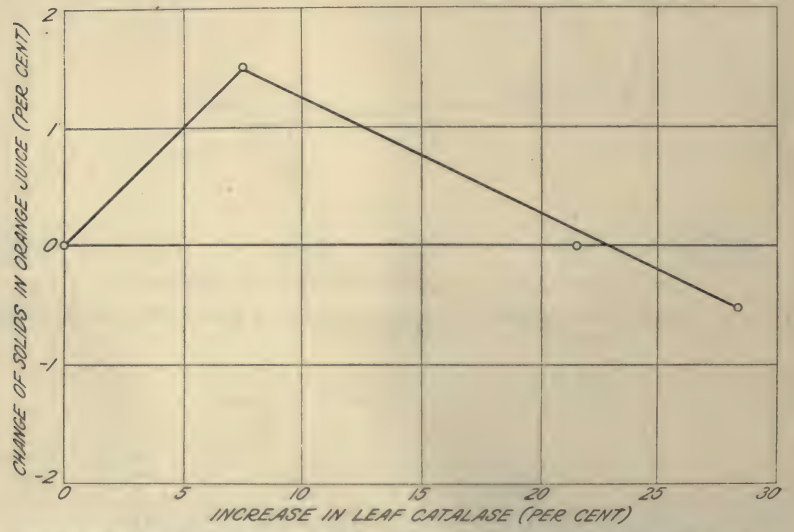


FIGURE 5.—Relation between soluble solids of orange juice at maturity and catalase activity of the leaves during the season

EFFECT OF ARSENICALS ON ORANGES WHEN LEAVES AND FRUIT WERE SPRAYED

As stated previously, it has been known for a considerable time that arsenic greatly changed fruit composition. In order to determine just how much effect various quantities of arsenic did have on fruit composition, many analyses have been made both of the insecticide on the tree during the growing season and of the fruit at various stages of development. In most cases only the total quantity of arsenic remaining on the leaves and the composition of the fruit at maturity are shown.

METHOD OF MAKING DETERMINATIONS

The hydrogen-ion determinations were made by means of a Welch quinhydrone apparatus. Early in the season, when the fruit was small and the quantity of juice was insufficient for a titration, a half fruit was covered with quinhydrone and the contact and bridge placed in the macerated material. When the fruit contained more juice the acid determinations were made by titration against sodium hydroxide

(0.156 N) and the soluble solids determined by a Brix hydrometer. The latter methods are the standard methods used for making the

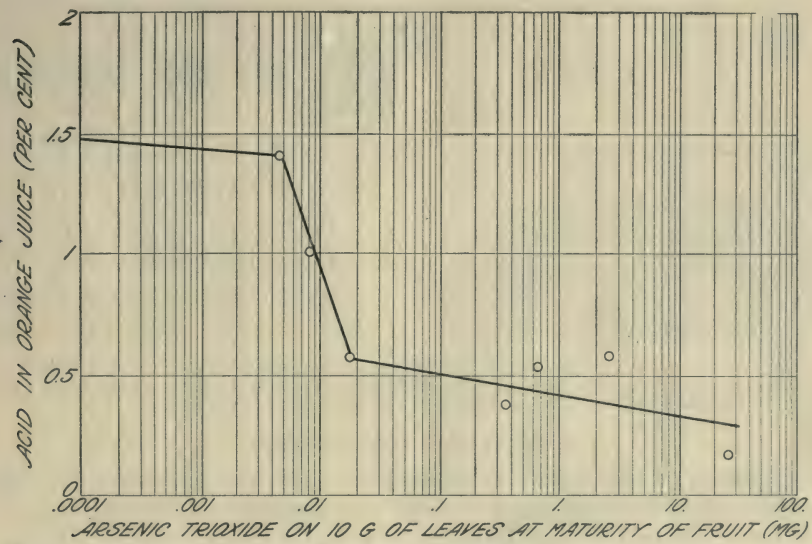


FIGURE 6.—Effect of lead arsenate on the acid in orange juice when arsenic trioxide has been present on the leaves in varying quantities during the growing season. Semilogarithmic

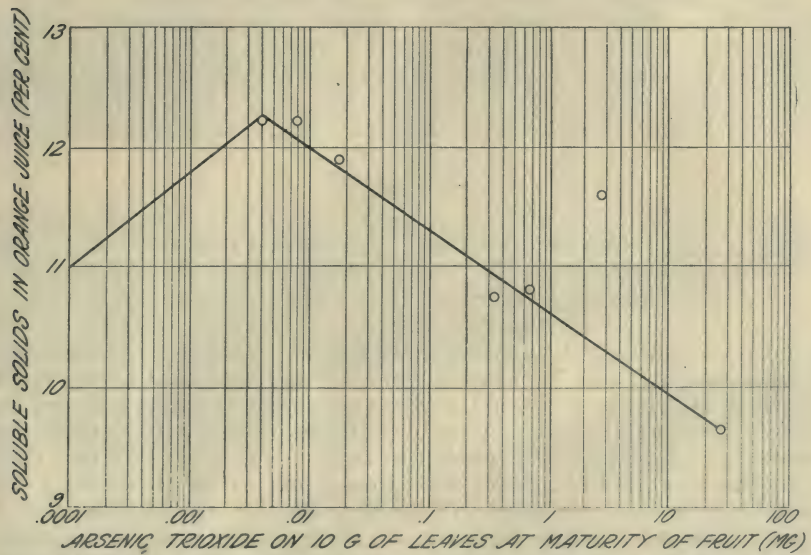


FIGURE 7.—Effect of lead arsenate on the soluble solids in orange juice when arsenic trioxide has been present on the leaves in varying quantities during the growing season. Semilogarithmic

maturity determinations called for by the State laws of Florida (*5*) The results of these analyses are shown in Table 11 and Figures 6 and 7

TABLE 11.—*The effect of lead arsenate on the acid, solids, ratio, and pH of orange juice when it has been present on the leaves in varying quantities throughout the growing season*

Spray treatment	Total arsenic trioxide per 10 g of green leaves at picking time	Acid in juice	Soluble solids in juice	Ratio of solids to acid	pH of juice
	Mg	*Per cent*	*Per cent*		
Check, no treatment	0	1.47	11.0	7.5	3.64
Lead arsenate, 2 pounds; water, 50 gallons, 1 year previous	.004	1.41	12.20	8.6	3.35
As above, 2 applications	.008	1.01	12.20	12.0	3.65
As above, 6 applications	.018	.59	11.90	20.2	3.99
Lead arsenate, 1 pound; water, 50 gallons, 6 months previous	.344	.38	10.74	28.3	5.17
Lead arsenate, 2 pounds; water, 50 gallons	[1].679	.54	10.81	20.0	4.66
As above, several applications	[1] 2.50	.59	11.60	19.7	3.99
30 pounds lead arsenate, applied to 1 tree	[1] 25.0	.17	9.65	56.7	5.00

[1] When arsenic was present in these quantities the leaves were injured and many of them fell, so a part of the arsenical effect was lost. These analyses were from leaves still on the trees.

HYDROGEN-ION CONCENTRATION

There was a very definite relation between the hydrogen-ion concentration of fruit at maturity and the quantity of arsenic used on the tree.

ACID IN FRUIT JUICE

Small quantities of arsenic reduced the acid in oranges very decidedly. When as much as 0.01 mg of arsenic (as arsenic trioxide) was left on 10 g of leaves at maturity, which was the quantity that would probably be left after a spraying of 8 ounces per 200 gallons of water, the maximum change was produced. Ten or one hundred times this quantity made no appreciable difference on the acid content of the fruit.

SOLUBLE SOLIDS IN FRUIT JUICE

Gray and Ryan (*9*) state that the sugars in fruit were not significantly changed, but work by Juritz (*11*) showed that there was a considerable decrease in sugars. While these points are apparently in disagreement, the data indicated that widely different quantities of arsenic were used by the two workers. Copeman stated that the sucrose was decreased but that there was no significant change in the total sugars (*3*). In the Florida work it was found that a very slight quantity of arsenic, 0.004 to 0.008 mg of arsenic trioxide, reduced the acid in the fruit juice considerably; the same quantity actually increased the soluble-solids content in fruit at maturity. When more than this quantity of arsenic was present on leaves at maturity the soluble solids were reduced in direct proportion to the quantity of arsenic present. When as much as 1 mg was present at maturity there was approximately a 10 per cent reduction in the soluble-solids content of juice of mature fruit.

RATIO OF ACID TO SOLUBLE SOLIDS

Since the effect of 0.008 mg of arsenic trioxide on orange leaves at fruit maturity was shown in the reduced acid content of fruit juice and slightly increased soluble-solids content, the ratio of acid to solids was obviously changed. When more than this quantity of arsenic

was present the solids were decreased; but because of a very great decrease in the acid also, the ratio was sometimes extremely high.

The writers are of the opinion that the fruit composition is changed only when the majority of the actively growing leaves on the tree at the time the fruit is growing have arsenic on them. For example, when arsenic was applied only to the old leaves of an orange tree it produced no effect, but later when it was applied to the young leaves the fruit composition was changed considerably. When lead arsenate was applied as late as eight months before some Temple oranges were analyzed and only the old leaves were present, there was no effect on the fruit composition, but where the new leaves had appeared before the lead arsenate was applied there was a very marked change in the composition of the fruit. When the leaves that have arsenic on them drop from the tree their effect on the fruit will be lost. If this happens during the first season, the next crop will be normal, but if the leaves stay on for more than a year the next crop will be affected also.

ARSENICAL ANALYSES OF FRUIT JUICE

Only a trace of arsenic was found [4] in a liter of orange juice when a tree had been given thirteen 1-quart applications of fruit-fly bait spray at 10-day intervals. This mixture contained 8 pounds of lead arsenate per 200 gallons. Eighteen daily applications of lead arsenate of the same quantity and the same strength were applied with the same result.

Arsenic as arsenic trioxide (As_2O_3) was found to the extent of 0.01 to 0.16 mg per liter of juice when 17 applications of 5 gallons of bait spray were made at 10-day intervals. Since the quantity of arsenic found in a liter of juice when the trees were very excessively sprayed was only a small fraction of a minimum medicinal dose, the juice from fruit trees normally sprayed could be in no way toxic for human consumption.

CHANGE OF PH OF ORANGE JUICE DURING GROWTH

The hydrogen-ion concentration was normally low when the fruit was small, but as the fruit grew the acid increased very rapidly. When the trees were treated with arsenic the change took place, but the acid content did not ever get so high as in untreated fruit. After the acid had reached its maximum it began to decrease, and on the trees that had been sprayed with arsenic the change was much more rapid than on those unsprayed. This is shown in Table 12 and Figure 8.

TABLE 12.—*Effect of lead arsenate when it is present on the leaves during the growing season, on the rate of development and disappearance of acid in oranges*

[Trees sprayed June 6, 1930]

Month of analysis	Arsenic trioxide per 10 g of sprayed leaves	pH of arsenical-sprayed fruit	pH of unsprayed fruit	Month of analysis	Arsenic trioxide per 10 g of sprayed leaves	pH of arsenical-sprayed fruit	pH of unsprayed fruit
	Mg				*Mg*		
June	3.10	4.55	4.60	September	0.54	4.08	3.28
July	1.47	3.03	2.90	October	.62	4.32	3.72
August	.86	3.53	3.07	November	.33	5.32	4.25

[4] MCBRIDE, O. C., MARLOWE, R. H., and BASSETT, I. P. Op. cit.

EFFECT OF ARSENIC NOT SYSTEMIC

It has been stated by other workers that the effect of arsenic on citrus trees was systemic. Gray and Ryan (*9*) stated that arsenic affected the entire tree if only a part was sprayed. This was also the opinion of Juritz (*11*). Yothers (*17*) reported that only the sprayed part of the tree was affected. In the present work the writers corroborated Yothers's statement that the effect was not systemic, since all the data obtained were the result of spraying half-trees and using the unsprayed part as a check.

RELATION BETWEEN TIME ARSENICAL SPRAY REMAINED ON LEAVES AND ITS EFFECT ON CITRUS FRUIT

Juritz (*11*) and Copeman (*3; 4, p. 144*) have stated in their works that the effect of arsenic persisted for more than one year. All the work done by these men was carried on under arid conditions.

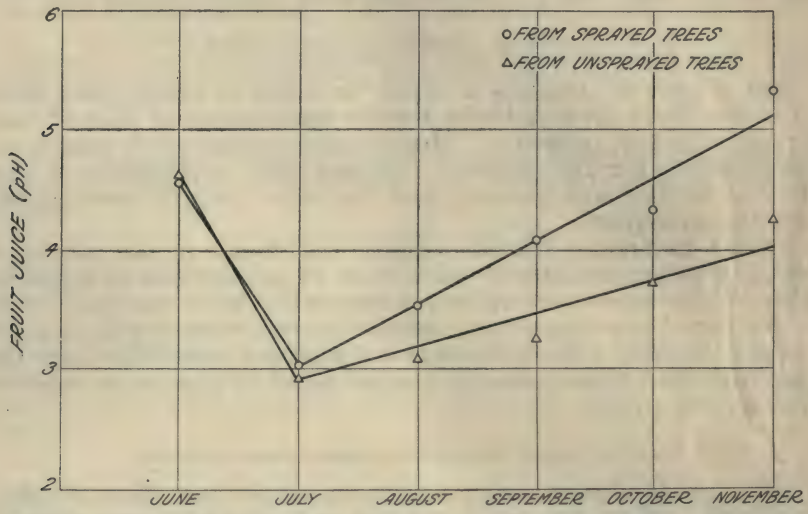


FIGURE 8.—Effect of lead arsenate on the rate of development and disappearance of acid in oranges when it is present on the leaves during the growing season. The trees were sprayed June 6

Experiments conducted in Florida, where the rainfall is approximately 55 inches per year, showed that the effect also persisted for about the same length of time. Fruit from trees heavily sprayed in May showed the effect throughout their growing season and until the fruit was harvested 10 or 12 months later. Fruit from trees sprayed several times during the growing season showed only a slight effect 18 months after the last spraying. At the end of 2½ years, however, fruit from sprayed and unsprayed trees was identical.

It was found that when applications of arsenic were made to actively functioning leaves the effect was almost immediately shown in the fruit. When an application of lead arsenate was made to Lue Gim Gong oranges as late as September, an analysis made one and one-half months later showed that the acid was reduced to 39 per cent of normal as shown by the checks.

SUMMARY

No noticeable effect on the fruit, tree, or undergrowth of a grapefruit tree was produced by 60 spray applications of one-half pound each of lead arsenate in 7½ gallons of water to the soil under the tree. The applications were made over a period of one and one-half years, and at the end of that time there were 2,000 parts of arsenic trioxide per million in the first 2 inches of soil, while only a trace was present in the leaves. Likewise, there was no effect on the fruit, tree, or undergrowth of an orange tree after 14 applications of one-half pound of lead arsenate each in 7½ gallons of water, even though there were 1,800 parts of arsenic trioxide per million in the first 2 inches of soil.

One year after the last application an analysis of the soil under the grapefruit tree was again made, and 1,800 parts per million was found in the first 2 inches of soil, and even at that time the tree, fruit, and undergrowth were normal.

When lead arsenate was sprayed on orange leaves a diminishing supply of water-soluble and insoluble arsenic was present for a year later. A tree sprayed with 8 pounds of lead arsenate per 200 gallons of sirup-sugar mixture had 0.34 mg of soluble arsenic as arsenic trioxide and 2.76 mg of insoluble arsenic on 10 g of green leaves immediately after spraying. At the end of six months the water-soluble arsenic had decreased to 0.005 mg and the insoluble to 0.19 mg.

An analysis of the wood, blossoms, and small fruit showed that arsenic was evidently translocated to these parts of the tree, for arsenic was present in quantities ranging from a trace to 6.9 mg of arsenic trioxide per kilogram of sample.

Soluble arsenic (measured as arsenic trioxide) present on leaves in quantities of 0.01 mg per 10 g of leaves stimulated respiration slightly, but when more than 1 mg was present on 10 g of leaves the respiration increase ranged from 50 to 75 per cent and the leaves usually fell.

When soluble arsenic was present at 0.01 mg of arsenic trioxide per 10 g of leaves the catalase activity was stimulated, but when quantities greater than this were present the catalase activity was decreased until, when as much as 1 to 10 mg was present, it was almost stopped.

When arsenic was present on the leaves, not so much acid formed in the fruit, and what was formed disappeared more rapidly than in the unsprayed fruit. When as much as 0.01 mg total arsenic trioxide was present on 10 g of green leaves at maturity, the maximum reduction without injury to the tree in fruit acid was produced. The hydrogen-ion concentration of fruit juice from trees that had been sprayed was much lower than that of juice from unsprayed trees.

The solids of fruit juice were somewhat increased when as little as 0.008 mg of arsenic trioxide was present, but when more than this quantity was present the solids were decreased. In this case also, approximately the same quantity of arsenic that stimulated the catalase activity caused the solids in the juice to be increased.

The ratio of acids to solids was very markedly affected by arsenic on the leaves. When as much as 0.01 mg of arsenic trioxide per 10 grams of leaves was present the ratio was only a little above normal, but a slight increase over this caused the ratio to rise to 20 to 1. When so much arsenic was present that the leaves dropped, the arsenic was eliminated from the tree and the fruit was less affected.

When the trees were sprayed seventeen times with 5 gallons per application a maximum of 0.16 mg of arsenic trioxide per liter of juice was found.

Experiments made by the writers have demonstrated that the effect of arsenic is not systemic, only the sprayed part of a tree being affected.

The effect of spraying with arsenicals is shown almost immediately and persists to a slight degree for about 18 months. After 2½ years, however, it has entirely disappeared.

LITERATURE CITED

(1) ANONYMOUS.
1926. SPOILING FRUIT WITH ARSENIC. Citrus Leaf 66:6–7.

(2) ASSOCIATION OF OFFICIAL AGRICULTURAL CHEMISTS.
1930. OFFICIAL AND TENTATIVE METHODS OF ANALYSIS . . . ED. 3, 593 p. illus. Washington, D. C.

(3) COPEMAN, P. R. V. D. R.
1927. SOME EFFECTS DUE TO THE SPRAYING OF FRUITS. So. African Jour. Sci. 24:198–203.

(4) ———
1931. CHANGES IN THE COMPOSITION OF ORANGES DURING RIPENING. Roy. Soc. So. Africa, Trans. 19:107–167, illus.

(5) FLORIDA STATE HORTICULTURAL SOCIETY.
1894. DISCUSSION ON CITRUS INSECTS AND INSECTICIDES. Fla. State Hort. Soc. Proc. 7:79–84.

(6) FLORIDA, LAWS, STATUTES, [etc.]
1925. GENERAL ACTS AND REGULATIONS ADOPTED BY THE LEGISLATURE OF FLORIDA. Ch. 10103, p. 162–167.

(7) ———
1929. GENERAL ACTS AND REGULATIONS ADOPTED BY THE LEGISLATURE OF FLORIDA. Ch. 13584, p. 70–76.

(8) ———
1929. GENERAL ACTS AND REGULATIONS ADOPTED BY THE LEGISLATURE OF FLORIDA. Ch. 14485, p. 937–939.

(9) GRAY, G. P., and RYAN, H. J.
1921. REDUCED ACIDITY IN ORANGES CAUSED BY CERTAIN SPRAYS. Calif. Dept. Agr. Mo. Bul. Spec. Chem. No. 10:11–33.

(10) HAWKINS, L. A., and BARGER, W. R.
1927 EFFECT OF ARSENICAL SPRAYS ON ORANGES. Citrus Leaf 71:11.

(11) JURITZ, C. F.
1925. EFFECTS OF SPRAYING CITRUS TREES ON THE COMPOSITION AND FLAVOUR OF THE FRUIT. Union So. Africa Dept. Agr. Jour. 11:240–243.

(12) LYON, C. J.
1927. ARSENATE AS A CATALYST OF OXIDATION. Jour. Gen. Physiol. 10:617–622, illus.

(13) MILLER, R. L., and MCBRIDE, O. C.
1931. EXPERIMENTS WITH COPPER CARBONATE, LEAD ARSENATE, AND OTHER COMPOUNDS AGAINST THE MEDITERRANEAN FRUIT FLY IN FLORIDA. Jour. Econ. Ent. 24:1119–1131, illus.

(14) NELSON, E. M., and MOTTERN, H. H.
1932. EFFECT OF LEAD ARSENATE SPRAY ON THE COMPOSITION AND VITAMIN CONTENT OF ORANGES. Amer. Jour. Pub. Health 22:587–600.

(15) SINGLETON, G.
1929. FACTORS AFFECTING THE MATURITY OF CITRUS FRUITS. Fla. State Hort. Soc. Proc. 42:105–109.

(16) TAKAHASHI, I.
1928. [EFFECT OF ARSENICAL SPRAYS ON CITRUS FRUITS.] Jour. Okitsu Hort. Soc. 23:93–101. [In Japanese.]

(17) YOTHERS, W. W.
1927. THE EFFECT OF ARSENIC ON THE COMPOSITION OF CITRUS FRUITS. Citrus Indus. 8 (11):11, 14.

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. . . . . Price 5 cents

TECHNICAL BULLETIN No. 349 MARCH, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

ANALYSIS OF THE ADVANCED REGISTRY RECORDS OF 611 DAUGHTERS OF 51 AYRSHIRE SIRES

By M. H. FOHRMAN, *Senior Dairy Husbandman*, and R. R. GRAVES, *Chief, Division of Dairy-Cattle Breeding, Feeding, and Management, Bureau of Dairy Industry*

CONTENTS

	Page
Introduction	1
Source of data and material used	2
Analysis of records of milk production	2
Comparative statistics on dams and daughters	2
Groups of sires with daughters having highest average production and highest average increase over dams	7
Individual sires in relation to milk records of their daughters	8
Full-sister groups of daughters	22
Maternal half sisters	25
Significance of correlation coefficients of milk production of dams and daughters	28
Influence of milk record of sire's dam	29
Half sisters of the sires	31
Methods of mating	35
Combinations of sires in relation to their influence on milk production	35
Analysis of records of butterfat test	36
Groups of sires with daughters having highest average butterfat test and highest average increase in test over dams	39
Individual sires in relation to butterfat test of their daughters	41
Significance of correlation coefficients and coefficients of variability of butterfat test of dams and daughters	50
Full-sister groups of daughters	52
Influence of butterfat test of sire's dam	53
Sires that increased both quantity of milk and percentage of butterfat	55
Independent inheritance of quantity of milk and percentage of butterfat	57
Summary and conclusions	57

INTRODUCTION

This bulletin is the second publication of a series based on the studies made of the advanced-registry and register-of-merit records of the various breeds of dairy cattle, the first [1] being published in 1926.

The factors that determine the quantity of milk production are inherited independently of those that determine the percentage of butterfat in the milk. It seemed logical, therefore, to study the milk production and the butterfat percentage in these records separately, rather than to study their combined results as represented by the butterfat-production records.

The animals in this study have proved to be so heterozygous in genetic make-up that the statistical analysis of their records has been very difficult from the standpoint of the study of heredity. Environment enters largely into the making of these official records,[2] and this also detracts from their usefulness in inheritance studies. Because records may be discontinued at any time, cows adversely

[1] GRAVES, R. R. TRANSMITTING ABILITY OF TWENTY-THREE HOLSTEIN-FRIESIAN SIRES. U. S. Dept. Agr. Bul. 1372, 32 p., illus. 1926.

[2] FOHRMAN, M. H. OFFICIAL RECORDS AS MATERIAL FOR STUDYING INHERITANCE OF MILK AND BUTTERFAT PRODUCTION. Jour. Dairy Sci. 9:286–292. 1926.

155872°—33——1

affected by environment are usually withdrawn from test, which further distorts the effect of environment.

At the time these records were made, the rules for entry into the advanced registry required a minimum production of 6,000 pounds of milk and 214 pounds of butterfat for cows calving at or before 2 years of age, and 8,500 pounds of milk and 322 pounds of butterfat for those calving at 5 years of age or older, with graded requirements for intermediate ages.[3] This rule automatically excluded the cows that failed to reach the required production and introduces another disturbing factor. Gowen,[4] by a devious method, estimates that not more than 28.3 per cent of the cows are excluded from the advanced registry by the requirements for milk yield, but this figure seems rather high.

Although the records analyzed in this study were all completed years ago, they show the results of dairy-cattle breeding practices of that period, and any information which they yield can be incorporated in our present meager fund of knowledge regarding practical dairy-cattle breeding. This study of the practices followed by leading breeders of Ayrshire cattle during the period reviewed strengthens the theory that substantial improvement in dairy-cattle breeding can be made only by a better basis of selecting herd sires.

SOURCE OF DATA AND MATERIAL USED

This bulletin gives an analysis of the records of 611 advanced-registry daughters of 51 Ayrshire bulls, and the records of the dams of these daughters. The material was taken from the Ayrshire Record Advanced Registry [5] and includes only the tested daughters of bulls having at least six record daughters from dams with records. This was also the basis of sire selection used in the study reported in the first publication of this series; but since the work was begun, Davidson [6] has demonstrated that for the Jersey breed, on the average, 6 is the smallest number of first-tested daughters whose average production closely approximates the average production of the first 15 daughters of a sire, and that the average production and variability among the productions of the first 15 tested daughters are representative of the average production and variability among the productions of any larger number of the sire's daughters. While the method of selection used in this study did not always include the first six tested daughters, it is believed that each group of daughters used is fairly representative of the get of the sire.

ANALYSIS OF RECORDS OF MILK PRODUCTION

COMPARATIVE STATISTICS ON DAMS AND DAUGHTERS

These 611 daughters are the offspring of 452 dams, but for comparative study of dams and daughters the records of the dams are repeated as often as the dams are represented by daughters. The milk records have all been corrected to a uniform age basis by the

[3] AYRSHIRE BREEDERS' ASSOCIATION. THE AYRSHIRE RECORD ADVANCED REGISTRY. v. 1, p. 9. Brandon, Vt. 1917.

[4] GOWEN, J. W. MILK SECRETION; THE STUDY OF THE PHYSIOLOGY AND INHERITANCE OF MILK YIELD AND BUTTERFAT PERCENTAGE IN DAIRY CATTLE. p. 137. Baltimore. 1924.

[5] AYRSHIRE BREEDERS' ASSOCIATION. Op. cit., also vols. 2–3.

[6] DAVIDSON, F. A. MEASURING THE BREEDING VALUE OF DAIRY SIRES BY THE RECORDS OF THEIR FIRST FEW ADVANCED REGISTRY DAUGHTERS. Ill. Agr. Expt. Sta. Bul. 270, pp. 545–566, illus. 1925.

use of factors developed from all initial records included in the Ayrshire Record Advanced Registry.[7]

Figure 1 shows the distribution of the dams (the actual number and weighted number), and their 611 daughters, according to milk production.

Table 1 lists the statistical constants for the generations studied.

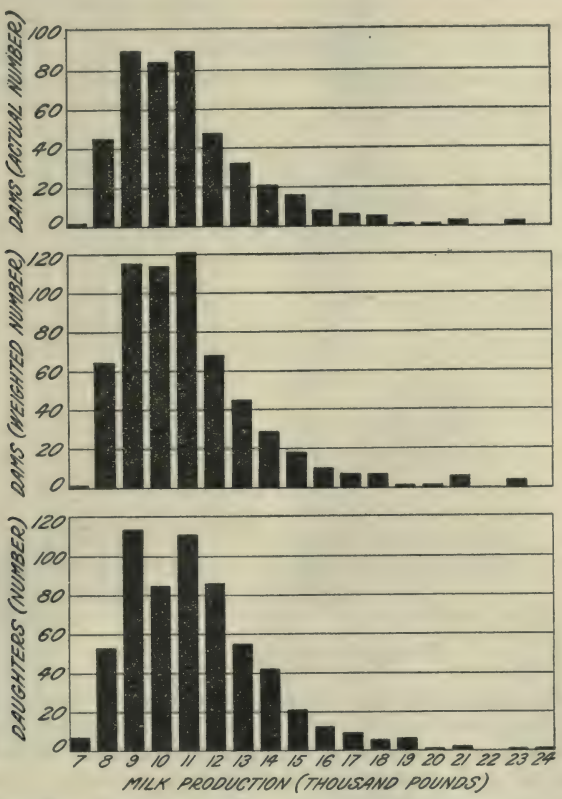


FIGURE 1.—Distribution of 452 dams (actual and weighted numbers) and their 611 daughters, according to milk production

TABLE 1.—*Statistical constants of milk production of the daughters and their dams*

Group	Average milk production	Animals above average	Animals below average	Standard deviation	Coefficient of variability
	Pounds	*Number*	*Number*	*Pounds*	*Per cent*
452 dams [1]	11,524±79	179	273	2,487±56	21.58±0.49
611 dams [2]	11,568±70	246	365	2,564±49	22.16± .43
611 daughters	11,732±69	263	348	2,510±48	21.39± .41

[1] Actual number. [2] Weighted number.

The 611 daughters have an average age-corrected record of 11,732 pounds of milk, whereas their dams average 11,568 pounds. The difference of 164 pounds of milk represents the increase in producing ability achieved in one generation of breeding. This increase amounts

[7] AYRSHIRE BREEDERS' ASSOCIATION. Op. cit., v. 1-3.

to 1.42 per cent, a rather slight rate of advance; and it is possible that at least part of this increase may be attributed to the ever-growing knowledge of methods of feeding and handling cows on test.

Table 2 shows the relationship of the milk-production records of dams and daughters. The correlation between the records of all dams and daughters is $+0.262 \pm 0.015$.

TABLE 2.—*Correlation surface for yearly milk-production records of the 611 daughters and their dams*

Yearly milk records of dams (pounds)	Number of daughters in milk-production class of—																		
	24,000 pounds	23,000 pounds	22,000 pounds	21,000 pounds	20,000 pounds	19,000 pounds	18,000 pounds	17,000 pounds	16,000 pounds	15,000 pounds	14,000 pounds	13,000 pounds	12,000 pounds	11,000 pounds	10,000 pounds	9,000 pounds	8,000 pounds	7,000 pounds	Total
24,000																			0
23,000											2		2						4
22,000																			0
21,000									2		1	1	2						6
20,000	1																		1
19,000						1													1
18,000							1			1		2	1		1	1			7
17,000				1								2	1	1	2				7
16,000								1	2		2	1	2		1	1			10
15,000		1									1	3	3	3	3	3		1	18
14,000					1	1	1	1	1	5	3	4	4	1	1	2	4		29
13,000						2		1	1		4	3	6	8	7	8	4	1	45
12,000				1		1	1			2	6	8	10	12	4	20	2	1	68
11,000								2	3	4	7	8	22	22	20	21	10	2	121
10,000						1	1			4	10	9	11	23	20	20	15		114
9,000							1	1	3	3	4	10	16	29	14	22	11	1	115
8,000								3		2	2	3	6	12	12	16	7	1	64
7,000												1							1
Total	1	1	0	2	1	6	5	9	12	21	42	55	86	111	85	114	53	7	611

EFFECT OF FEMALE SELECTION

In order to illustrate further the influence of the milk-producing capacity of the dams on the offspring when the sires are selected at random, the dams in this study have been divided into two groups on the basis of their yearly milk-production records. The 246 dams whose milk-production records are higher than the average for all the dams, 11,568 pounds, make up one group and will be referred to hereafter as the grade A dams. The 365 dams whose records are below the average make up the other group and will be referred to as the grade B dams. Similarly, the 611 daughters have been divided into two groups with the 11,732-pound average for all daughters as the dividing line. The 263 daughters whose records are above the average will be called grade A daughters, and the 348 daughters whose records are below the average will be called grade B daughters.

The grade A dams constitute only 40 per cent of all the dams, but they produced 51 per cent, or 134, of the 263 grade A daughters. Although these dams averaged 13,892 pounds of milk, their 246 daughters averaged only 12,361 pounds, and although the average for the grade A dams is 2,324 pounds above the average for all the dams, the average of their daughters is only 629 pounds above the average for all the daughters. Only 73 of the daughters of the grade A dams, or about 30 per cent, exceeded their dams in milk production, while 173 failed to do so.

The distribution of the grade A dams and their daughters in relation to their milk production is shown in Figure 2.

The grade B dams, which comprise 60 per cent of all the dams in the study, produced 129 of the 263 grade A daughters, or 49 per cent, and 236 grade B daughters. Although 253 of the daughters of grade B dams exceeded their dams in milk production, only 129, or 35 per cent, were above the average of the 611 daughters. The average milk production of the grade B dams was 10,002 pounds, which is 1,566 pounds below the average of all the dams; whereas the average of their 365 daughters was 11,309 pounds, which is only 423 pounds below the average for all daughters.

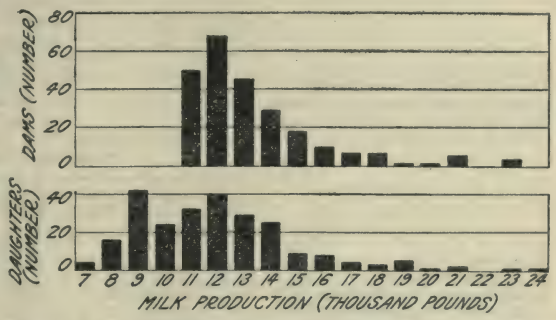


FIGURE 2.—Distribution of 246 grade A dams and their daughters according to milk production

The distribution of the grade B dams and their daughters, in relation to their milk production, is shown in Figure 3.

To summarize briefly, when the sires are selected at random, and the dams are arbitrarily divided at the line of average production, the records of the daughters in each group tend strongly to approach the average production of all the daughters.

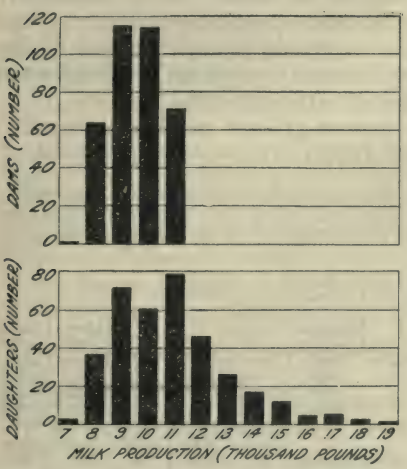


FIGURE 3.—Distribution of 365 grade B dams and their daughters according to milk production

This tendency is shown by the distributions in Table 2, and is emphasized strongly in the extremely high and low-producing groups. There are 54 dams with records above 15,000 pounds of milk, and only 5 have daughters with records above their own. Sixty-five dams produced less than 9,000 pounds of milk, and only 5 of their daughters failed to exceed the dams' records.

In the daughter group, 58 have records above 15,000 pounds of milk, and only 6 of these produced less than their dams; 60 of the daughters have records below 9,000 pounds of milk, and only 3 of them made more than their dams. These facts would have some bearing on the selection of females for breeding purposes.

The figures in Table 3 indicate a closer correlation between high-producing dams and their daughters than between low-producing dams and their daughters. The same is true of high-producing daughters and their dams as compared to low-producing daughters and their dams.

TABLE 3.—*Correlation between high-producing dams and their daughters, low-producing dams and their daughters, high-producing daughters and their dams, and low-producing daughters and their dams*

Group	Daughter-dam pairs	Production of dams		
		Average milk production	Standard deviation	Coefficient of variability
	Number	*Pounds*	*Pounds*	
Dams over 15,000 pounds milk	54	17,708±236	2,576±170	14.55±0.96
Dams under 9,000 pounds milk	65	8,647±17	213± 12	2.46±0.15
Daughters over 15,000 pounds milk	58	12,893±290	3,273±205	25.39±1.59
Daughters under 9,000 pounds milk	60	10,970±157	1,800±120	16.40±1.01

Group	Production of daughters			Correlation coefficient
	Average milk production	Standard deviation	Coefficient of variability	
	Pounds	*Pounds*		
Dams over 15,000 pounds milk	13,459±309	3,363±222	24.99±1.65	+0.223±0.055
Dams under 9,000 pounds milk	11,123±190	2,267±134	20.38±1.21	+.161± .059
Daughters over 15,000 pounds milk	17,254±181	2,045±128	11.85±0.74	+.322± .041
Daughters under 9,000 pounds milk	8,513± 29	333± 21	3.91±0.24	−.140± .064

Selection from the female side alone holds small promise for permanent improvement in milk production. Even if drastic selection is practiced, the results are certain to be disappointing, as the high level established by the original culling can only be maintained by continued close culling, which would result in tremendous sacrifice of females. On the other hand, with no further selection of sires than was practiced in choosing the sires of the 611 daughters in this study, the daughters of the lower-producing dams tend almost uniformly to exceed their dams in production; but this method of selecting sires fails to greatly raise the average of the whole group because of the fact that the sires used were not sufficiently good to raise or even maintain the production of the higher-producing dams.

The average production of the various groups of dams, together with the averages of their respective daughters, is shown in Table 4.

TABLE 4.—*Average milk production of the dams and their daughters in the various production groups, number of daughters above and below their dams in each group, and number of daughters above and below the average of all daughters in the study*

Milk production group	Daughter-dam pairs	Average milk production of—		Increase (+) or decrease (−) by daughters over dams	Daughters with records—				
		Dams	Daughters		Above their dams		Below their dams	Above average of all daughters	Below average of all daughters
	Number	*Pounds*	*Pounds*	*Pounds*	*Number*	*Per cent*	*Number*	*Number*	*Number*
23,000 pounds	4	23,821	13,631	−10,190	0	0	4	4	0
22,000 pounds									
21,000 pounds	6	21,428	14,217	−7,211	0	0	6	6	0
20,000 pounds	1	20,174	24,285	+4,111	1	100	0	1	0
19,000 pounds	1	19,387	19,809	+422	1	100	0	1	0
18,000 pounds	7	18,334	13,311	−5,023	0	0	7	5	2
17,000 pounds	7	17,349	13,353	−3,996	1	14	6	4	3
16,000 pounds	10	16,471	13,703	−2,768	1	10	9	8	2
15,000 pounds	18	15,463	12,175	−3,288	1	6	17	9	9
14,000 pounds	29	14,425	13,560	−865	12	41	17	22	7
13,000 pounds	45	13,432	11,695	−1,737	9	20	36	18	27
12,000 pounds	68	12,495	11,832	−663	23	34	45	32	36
11,000 pounds	121	11,477	11,530	+53	58	48	63	49	72
10,000 pounds	114	10,491	11,304	+813	66	58	48	38	76
9,000 pounds	115	9,503	11,315	+1,812	93	81	22	45	70
8,000 pounds	64	8,658	11,093	+2,435	59	92	5	20	44
7,000 pounds	1	7,974	13,004	+5,030	1	100	0	1	0
Total or average	611	11,568	11,732	+164	326	53	285	263	348

Heterosis, or hybrid vigor, may account for some of the higher-producing dams. It is probable, judging from these data, that most of the sires have a heterozygous genetic make-up, and the matings of these animals of mixed inheritance would result in offspring which tend to revert to the average of the parent stock in production. If it is assumed that the low-producing dams still carry some of the factors for high production, then from matings with the same heterozygous sires there should be some increase in the producing ability of the offspring, which is what occurred. Four of the dams whose production was above 15,000 pounds of milk dropped daughters which were considerably better producers, and in these instances there is evidence of an inheritance of the factors for high production from both of the heterozygous parents. Twenty of the dams with milk records below 9,000 pounds have daughters which failed to exceed their dams by 1,000 pounds of milk or more. Those producing much less than their dams would have been excluded from the advanced registry by the breed requirements and are not available for this study. The 121 daughters of the dams with a milk production of 11,000 pounds form an interesting group. Twenty-two are in the same class as their dams, 46 are in a higher class, and 53 in a lower class.

GROUPS OF SIRES WITH DAUGHTERS HAVING HIGHEST AVERAGE PRODUCTION AND HIGHEST AVERAGE INCREASE OVER DAMS

Because of the limited number of offspring of the individual sires it was deemed best to study them first in groups.

One group of 10 sires, having a total of 96 daughters, was selected on the basis of the high average production of the daughters of each sire. Taking the daughters of each sire as a unit, the average milk production ranged from 14,994 to 12,996 pounds. Mathematical constants for this group are listed in line 1, Table 5.

TABLE 5.—*Statistical data on the daughters of two groups of sires, one group selected on the basis of the high average production of their daughters, the other on the basis of the greatest average increase in production by the daughters over their dams*

Group	Daughter-dam pairs	Production of dams		
		Average milk production	Standard deviation	Coefficient of variability
	Number	*Pounds*	*Pounds*	*Per cent*
10 sires with highest average daughters	96	12, 221±172	2, 505±122	20. 50±1. 00
10 sires with greatest average increase by daughters over dams	84	10, 831±163	2, 217±115	20. 47±1. 07

Group	Production of daughters			
	Average milk production	Standard deviation	Coefficient of variability	Coefficient of correlation
	Pounds	*Pounds*	*Per cent*	
10 sires with highest average daughters	13, 447±187	2, 724±133	20. 26±0. 99	+0. 383±0. 026
10 sires with greatest average increase by daughters over dams	12, 116±175	2, 382±124	19. 66±1. 02	+ . 440± . 023

The interesting fact about the first 10 sires is that although the 96 dams to which they were mated averaged 653 pounds more milk than the average production of all dams in this study, their daughters exceeded the average of all the daughters by 1,715 pounds. The average increase by the daughters of these sires over their dams was 1,226 pounds, and 62 daughters were better producers than their dams.

The other group of 10 sires was selected on the basis of average increase in milk production which the daughters of each sire had shown over the records of their dams. The sires selected were those whose daughters showed the greatest average increase. The 84 daughters of these sires averaged an increase of 1,285 pounds over the average of the dams. Mathematical constants for this group are listed in line 2, Table 5.

A comparison of the results obtained with both groups of good sires and with the entire class of 51 sires is shown in Table 6.

TABLE 6.—*Results of mating the 51 sires with the grade A and B dams, compared with the results of mating two selected groups of sires with grade A and B dams*

Number of sires and number and grade of dams with which each group of sires was mated	Average milk production of—		Increase (+) or decrease (−) by daughters over dams
	Dams	Daughters	
	Pounds	*Pounds*	*Pounds*
51 sires:			
611 grade A and B dams	11,568	11,723	+164
246 grade A dams	13,892	12,361	−1,531
365 grade B dams	10,002	11,309	+1,307
10 best sires, selected on the basis of high average production of their daughters:			
96 grade A and B dams	12,221	13,447	+1,226
48 grade A dams	14,184	14,130	−54
48 grade B dams	10,257	12,764	+2,507
10 best sires selected on the basis of greatest average increase in production by daughters over dams:			
84 grade A and B dams	10,831	12,116	+1,285
20 grade A dams	13,841	13,736	−105
64 grade B dams	9,890	11,609	+1,719

When the 51 sires were mated to grade A dams, 30 per cent of the daughters were better than the dams, and when mated to grade B dams, 70 per cent of the daughters were better than the dams.

When the 10 best sires by the first method of selection (high-average daughters) were mated to grade A dams, 50 per cent of the daughters were better producers than the dams, and when mated to grade B dams 80 per cent of the daughters were better than the dams.

The other 10 best sires, because of the basis of selection (high average increases), were able to get higher percentages of daughters better than the dams, but it is also true that both the grade A and grade B dams in these matings averaged below those mated with the preceding 10 sires.

INDIVIDUAL SIRES IN RELATION TO MILK RECORDS OF THEIR DAUGHTERS

With reference to the individual sires, there is a paucity of convincing data, partly because of the limited number of daughters sired by each of the bulls, and also because of the additional evidence of the heterozygous genetic make-up of the animals in the study. It is

difficult to prove the existence of a pronounced upward trend in milk production in the get of any single sire or that any sire was homozygous for high milk production. Considering the sires individually, the the most striking tendency noted is the ability of the bulls to sire daughters inferior to the high-producing dams and superior to the low-producing dams to which they are mated. This emphasizes the heterozygous genetic make-up of both males and females.

For comparative purposes the sires were ranked according to the method used in the study of Holstein-Friesian sires.[8] This method was based on consideration of the average yields of milk and butterfat of the daughters, the average increase or decrease in milk and butterfat production of the daughters compared to their dams, and the proportion of daughters which exceeded their dams in milk and butterfat yield. The Ayrshire sires were first ranked according to each of these considerations, and the sum of the individual rankings determined the final rank of each sire. This method of ranking sires was used because no better system has yet been offered, and furthermore, the ranking of sires is merely incidental to this study and not its fundamental object.

Table 7 shows the ranking of the 51 sires and the distribution of their daughters according to the level of milk production. The table also shows the average production of the daughters, the average production of their dams, the difference in average production, and the rank of each group of dams and daughters.

[8] GRAVES, R. R. Op. cit.

TABLE 7.—*Number of daughters by individual sires in each milk-production class, and average milk production and rank of daughters and dam*

Rank of sire [1]	Number of daughters in milk-production class of—																	Total daughters	Average milk production of daughters	Rank of daughters according to milk production	Average milk production of dams	Rank of dams according to milk production	Increase (+) or decrease (−) by daughters over dams	Rank of daughters by increase or decrease	Daughters with—	
	24,000 pounds	23,000 pounds	22,000 pounds	21,000 pounds	20,000 pounds	19,000 pounds	18,000 pounds	17,000 pounds	16,000 pounds	15,000 pounds	14,000 pounds	13,000 pounds	12,000 pounds	11,000 pounds	10,000 pounds	9,000 pounds	8,000 pounds	7,000 pounds							Increased production	Decreased production
																			Number	*Pounds*		*Pounds*		*Pounds*		*Number*	*Number*
1								1			2	1	1				1		6	13,482	4	11,977	19	+1,505	6	5	1
2				1							3	2	2	3		1			12	13,268	5	11,404	27	+1,864	2	8	4
3							1			3	3	2	3	3	1			1	17	13,240	7	11,464	25	+1,776	3	12	5
4		1				1						2	2	3	3		1		13	12,952	11	11,793	23	+1,159	11	9	4
5											3		1	1	1				6	13,108	9	11,180	33	+1,928	1	5	1
6									2			2	5	1	2		2		14	12,216	17	10,960	38	+1,256	9	12	2
7										1	2		1	2	1				7	12,996	10	11,958	21	+1,038	16	5	2
8	1							2		2		1	1	1	3	1	1		13	13,495	3	12,082	15	+1,413	8	8	5
9							1						1		2	3			7	11,472	27	9,705	49	+1,767	4	5	2
10						1			2	1			3						7	14,994	1	13,518	4	+1,476	7	5	2
11								1	2	2	5	8	8	7	5	7	3		48	12,251	16	11,192	32	+1,059	15	33	15
12						2		1	1	2	4	3	5	7	6	5	2		38	12,404	14	11,329	30	+1,075	14	26	12
13							1		1	2	2	1	1	1	1		1		11	13,685	2	12,851	6	+834	17	6	5
14													1	3	2		1		7	11,096	30	9,964	48	+1,132	13	5	2
15											1		1	3	3	2	1		10	11,489	26	10,664	42	+825	18	6	4
16							1						1	5	1	2			10	11,774	24	10,256	45	+1,518	5	8	2
17											1			4	1	2	1		9	10,621	41	9,439	51	+1,182	10	7	2
18						1					3	3	1	1		5			14	12,516	13	12,303	14	+213	24	9	5
19										1	1	6	2		1				11	13,238	8	13,550	3	−312	34	6	5
20									1		2	1	1	1	1	1	1	1	10	11,981	21	11,392	28	+589	19	5	5
21													2	4	2	2	1		11	10,902	36	10,367	44	+535	20	8	3
22								1		3		2	2	2	2		4		16	12,196	18	11,040	35	+1,156	12	9	7
23				1							1	4	2	6	4	2			20	12,177	19	12,352	13	−175	32	11	9
24												1	3	1		1			6	11,989	20	11,970	20	+19	27	3	3
25											1	1	3	3	2	2	1		13	11,258	28	11,382	29	−124	31	7	6
26								1	1		1			1		2			6	13,257	6	12,780	8	+477	21	2	4
27									1	1	1	2	2	4	4	12	3	1	31	10,767	39	11,011	37	−244	33	17	14
28					1					1	1	2	1	3	2	1	1		13	12,382	15	12,406	11	−24	29	5	8
29													1	2	2	1			6	10,933	34	10,916	39	+17	28	3	3
30						1				1		1			1	1	1		6	12,849	12	12,814	7	+35	26	2	4
31													1	1	1	4	2		9	9,946	46	10,049	47	−103	30	6	3
32													2	1		3	4	1	11	9,688	49	9,643	50	+45	25	4	7
33												1	3	4	2	4			14	11,205	29	12,366	12	−1,161	43	7	7
34											1		2	1	2	2	1		9	11,028	32	10,696	41	+332	23	5	4

35								1					3	3	1	7			15	11,089	31	11,768	22	−679	36	8	7
36							1		1		3	2	3	10	3	4	3		30	11,806	23	12,622	9	−816	38	12	18
37								1						2	2	4			9	10,916	35	11,273	31	−357	35	2	7
38														3		3			6	10,504	43	10,103	46	+401	22	3	3
39														2	4	1	2		9	10,176	44	11,012	36	−836	39	4	5
40												1		1	3	4	1	1	11	9,965	45	11,058	34	−1,093	42	4	7
41													1	2	3	2	1		9	10,507	42	11,418	26	−911	40	3	6
42											1	1	3	2	1	2			10	11,868	22	13,047	5	−1,179	44	3	7
43											1	1	1	1	1	1	1		7	11,530	25	15,279	1	−3,749	51		7
44											1		1	1	1	3			7	10,933	33	14,118	2	−3,185	50		7
45													3		1	3			7	10,721	40	12,064	16	−1,343	46	2	5
46												1	2	1		1	1	1	7	10,851	37	12,049	17	−1,198	45	3	4
47												1			2	5	3	1	12	9,612	50	10,408	43	−796	37	2	10
48									1				1	1	4		3		10	10,786	38	12,442	10	−1,656	47	3	7
49													1	1		4	2		8	9,736	48	10,731	40	−995	41	2	6
50														1	1	3	1		6	9,748	47	11,984	18	−2,236	49		6
51														1	1	2	3		7	9,531	51	11,635	24	−2,104	48	1	6

[1] This rank is arrived at by combining the relative standings of these sires on milk production, butterfat production, increase in milk and butterfat production by daughters over dams, and proportion of daughters better than dams in milk and butterfat production.

TABLE 8.—*Rank of sire and of sire's sire, milk production of sire's dam, and statistical constants on milk production of the daughters of the individual sires and of the dams of the daughters*

Rank of sire [1]	Daughters	Milk production of sire's dam	Rank of sire's sire [1]	Daughters			Dams			Coefficient of correlation
				Average milk production	Standard deviation	Coefficient of variability	Average milk production	Standard deviation	Coefficient of variability	
	Number	*Pounds*		*Pounds*	*Pounds*		*Pounds*	*Pounds*		
1	6	17,793	36	13,482± 760	2,758±537	20.46±3.98	11,977± 568	2,062±401	17.22±3.35	+0.750±0.120
2	12	12,969		13,268± 556	2,855±393	21.52±2.96	11,404± 357	1,833±252	16.07±2.21	+.023± .194
3	17			13,240± 383	2,344±271	17.70±2.05	11,464± 360	2,202±255	19.21±2.22	−.040± .163
4	13	18,110		12,952± 736	3,939±521	30.41±4.02	11,793± 610	3,262±431	27.66±3.66	+.443± .150
5	6	9,569	4	13,108± 416	1,511±294	11.53±2.25	11,180± 164	596±116	5.33±1.04	+.301± .250
6	14			12,216± 402	2,228±284	18.24±2.33	10,960± 560	3,105±396	28.33±3.61	+.235± .170
7	7			12,996± 446	1,749±315	13.46±2.43	11,958± 355	1,394±251	11.66±2.10	+.213± .243
8	13			13,495± 785	4,198±555	31.11±4.12	12,082± 511	2,733±361	22.62±2.99	+.690± .098
9	7	12,570		11,472± 749	2,936±529	25.59±4.61	9,705± 240	940±240	9.69±1.75	+.432± .207
10	7	21,331	20	14,994± 582	2,283±411	15.23±2.75	13,518± 871	3,417±616	25.28±4.56	+.729± .119
11	48	11,781		12,251± 224	2,206±158	18.74±1.29	11,192± 225	2,312±159	20.66±1.42	+.439± .078
12	38			12,404± 294	2,691±208	21.69±1.68	11,329± 268	2,454±190	21.66±1.67	+.311± .098
13	11	12,349		13,685± 545	2,680±385	19.58±2.82	12,851± 670	3,295±474	25.64±3.69	+.429± .165
14	7	8,853	39	11,096± 309	1,211±218	10.91±1.97	9,964± 266	1,043±188	10.47±1.89	−.575± .170
15	10	21,324	11	11,489± 254	1,189±179	10.35±1.56	10,664± 328	1,539±232	14.43±2.18	+.498± .160
16	10			11,774± 489	2,294±489	19.48±2.94	10,256± 237	1,112±168	10.84±1.63	−.080± .211
17	9			10,621± 311	1,382±220	13.01±2.07	9,439± 212	942±222	9.98±1.59	−.303± .204
18	14	14,412	4	12,516± 484	2,674±341	21.36±2.72	12,303± 701	3,888±496	31.60±4.03	−.073± .179
19	11	21,733	2	13,238± 224	1,099±158	8.30±1.19	13,550± 777	3,820±549	28.19±4.05	+.370± .175
20	10	21,023		11,981± 610	2,858±431	23.85±3.60	11,392± 775	3,633±548	31.89±4.81	+.419± .176
21	11	11,212	8	10,902± 246	1,211±174	11.11±1.60	10,367± 281	1,382±199	13.33±1.92	−.408± .169
22	16			12,196± 483	2,863±341	23.47±2.80	11,040± 386	2,288±273	20.72±2.47	−.192± .162
23	20	14,227	11	12,177± 391	2,591±276	21.28±2.27	12,352± 377	2,498±366	20.22±2.16	+.476± .116
24	6	12,571	4	11,989± 417	1,516±295	12.64±2.46	11,970± 692	2,512±489	20.99±4.09	+.257± .257
25	13	21,733		11,258± 301	1,612±213	14.32±1.89	11,382± 271	1,451±192	12.75±1.69	−.230+ .177
26	6	15,382	12	13,257± 850	3,086±601	23.28±4.53	12,780± 767	2,788±543	21.82±4.25	+.572± .185
27	31			10,767± 249	2,057±176	19.10±1.64	11,011± 203	1,674±143	15.20±1.30	+.159± .118
28	13			12,382± 550	2,940±389	23.74±3.14	12,406± 387	2,066±273	16.57±2.19	+.264± .174
29	6	11,505	4	10,933± 257	933±182	8.53±1.66	10,916± 230	836±163	7.66±1.49	−.727± .129
30	6	13,750	4	12,849±1,083	3,936±766	30.63±5.96	12,814± 752	2,731±532	21.31±4.15	−.011± .275
31	9	9,719		9,946± 264	1,173±186	11.79±1.87	10,049± 216	959±152	9.54±1.52	+.581± .148
32	11			9,688± 311	1,528±220	15.77±2.27	9,643± 143	705±101	7.31±1.05	+.480± .156
33	14	13,506	11	11,205± 205	1,134±214	10.12±1.29	12,366± 750	2,805±358	22.68±2.89	−.611+ .112
34	9			11,028± 395	1,756±279	15.92±2.53	10,696± 323	1,437±228	13.43±2.14	+.207± .215
35	15			11,089± 364	2,092±258	18.87±2.32	11,768± 706	4,063±500	34.53±4.26	+.321± .080
36	30			11,806± 273	2,219±193	18.80±1.64	12,622± 342	2,774±242	21.98±1.91	+.455± .097
37	9	9,874	40	10,916± 582	2,589±412	23.72±3.77	11,273± 366	1,630±259	14.46±2.30	−.400± .188

38	6		22	10,505± 278	1,011±197	9.62±1.87	10,103± 395	1,436±280	14.21±2.77	−.715± .224
39	9			10,176± 192	852±135	8.37±1.33	11,012± 331	1,474±234	13.39±2.13	−.346± .197
40	11			9,965± 274	1,345±193	13.50±1.94	11,058± 348	1,710±246	15.46±2.22	−.537± .144
41	9	10,681	11	10,507± 282	1,253±199	11.93±1.90	11,418± 103	456± 72	3.99±0.63	−.322± .201
42	10	15,626		11,868± 339	1,588±240	13.38±2.02	13,047± 235	1,102±166	8.45±1.27	−.135± .209
43	7	12,583	3	11,530± 468	1,835±331	15.92±2.87	15,279± 853	3,347±603	21.28±3.84	+.831± .078
44	7	13,896	35	10,933± 487	1,912±345	17.49±3.15	14,118±1,113	4,364±787	30.91±5.57	+.937+ .031
45	7			10,721± 309	1,212±218	11.30±2.04	12,064± 590	2,313±417	19.17±3.46	+.199± .244
46	7	8,865	16	10,851± 513	2,012±363	18.54±3.34	12,049± 443	1,737±313	14.42±2.60	−.356± .222
47	12			9,612± 277	1,425±196	14.83±2.04	10,408± 231	1,184±163	11.38±1.57	+.206± .186
48	10			10,786± 362	2,015±304	18.68±2.82	12,442± 441	2,069±312	16.63±2.51	+.103± .190
49	8	11,920	7	9,736± 307	1,287±217	13.22±2.23	10,731± 295	1,235±208	11.51±1.94	−.232± .225
50	6	10,389		9,748± 253	918±179	9.42±1.83	11,984± 552	2,006±391	16.74±3.26	+.373± .236
51	7			9,531± 291	1,142±206	11.98±2.16	11,635± 534	2,095±378	18.01±3.25	+.214± .243

[1] The individual sires are referred to by the same number as the number of their rank given in Table 7.

Comparative studies of the various sires are rendered less valuable because of the differences in the number of daughters representing each sire and also because of the variation in the quality of the dams to which they were mated. Sire 11 [9] has 48 daughters, or eight times the minimum number which admitted 8 other bulls to the study. Sire 43 was mated with dams that averaged 15,279 pounds of milk, while sire 17 was mated to dams that averaged 9,439 pounds of milk. Any results of comparison of these sires would of necessity have to be modified by consideration of the transmitting tendencies of various grades of dams already discussed.

Table 8 shows the average milk production of the daughters of each sire and of the dams of the daughters, the standard deviation and coefficient of variability of each group, and the coefficient of correlation of the daughters of each sire with their dams. The table also shows the milk production of the sire's dam and the rank of his sire.

[9] The individual sires are referred to by the same number as the number of their rank given in Table 7.

Figures 4 and 5 show the milk-production records of the daughters of several sires and of their dams.

Sire 12 is fairly representative of the better bulls in this study, and he clearly shows the tendency, mentioned on page 5, to sire daughters inferior to the high-producing dams, and superior to the low-producing dams with which he was mated.

Sire 23 is of interest because of the variability in milk production shown by his 9 daughters from dams in the 11,000-pound class; and conversely, sire 36 is of interest because he produced 10 daughters with an average milk production of 11,000 pounds from dams with a wide range of production. In the case of sire 37, one of his lowest-

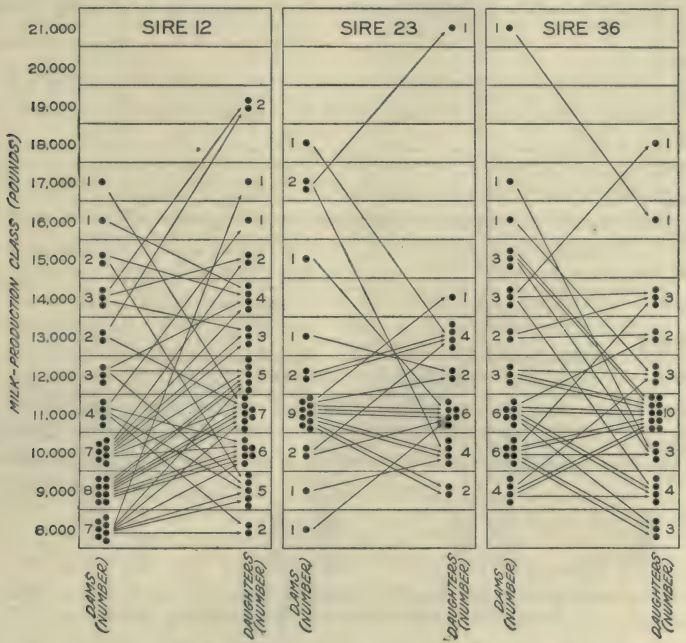


FIGURE 4.—Trend of milk production by daughters of three sires, as shown by the number of daughters, from dams in various milk-production classes

producing daughters is out of the highest-record dam to which he was mated, and his best daughter is out of one of the poorest dams. Sire 41 got daughters with a wide range of production from 8 dams in the 11,000-pound class. Sires 43 and 44 consistently lowered the milk production of the offspring of good dams, and the influence of these good dams is reflected in the high correlation between the daughters and the dams. (Table 8.) These two sires were without doubt decidedly lacking in ability to transmit the factors for high milk production to their daughters. The group of dams to which these sires were mated ranked first and second in average milk production (Table 7), and their offspring show the greatest average decrease. Even though these high-producing dams may be heterozygous, as has been suggested before, that fact alone is not enough to account for the uniform and large decline in producing ability shown by their offspring, and it must be conceded that these two sires are also at fault.

SIRES WITH GREATEST PROPORTION OF DAUGHTERS BETTER THAN THEIR DAMS

Individually these 51 sires showed ability to transmit a wide variation in producing capacity, but none was able to get daughters all of which exceeded their dams in milk production. The best showing in this particular was made by sire 6, 12 of his 14 daughters being better producers than their dams. This sire was mated to a mixed class of dams, one dam produced more than 21,000 pounds of milk, another more than 13,000 pounds, while the other 12 averaged 9,890 pounds,

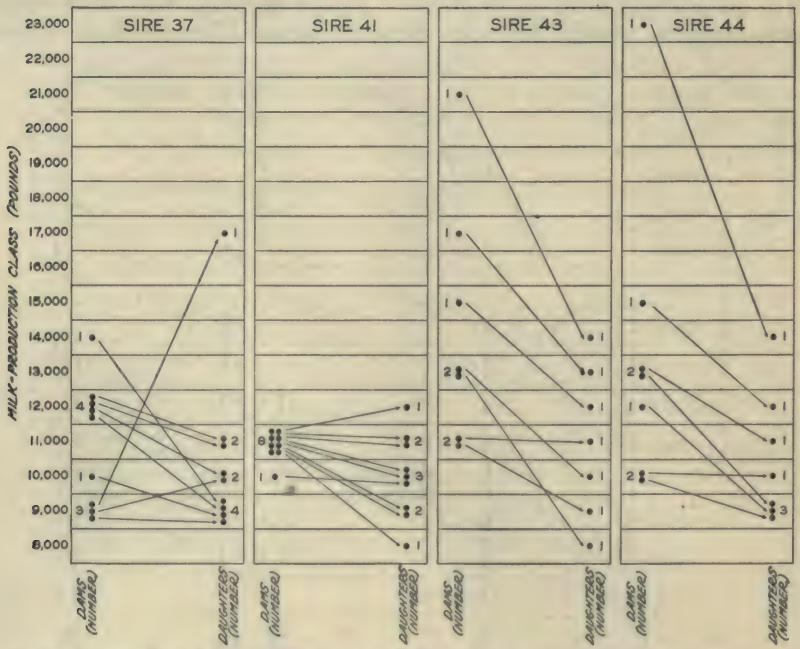


FIGURE 5.—Trend of milk production by daughters of four sires, as shown by the number of daughters, from dams in various milk-production classes

which would rank them low as a group. The offspring of sire 6 from the two high-producing dams were above the average in milk production, but their true value is best understood by comparing them with the get of other sires from these same dams. Each of this sire's daughters is the lowest producer of three maternal half sisters from these dams. His showing on the other 12 dams was very good and he evidenced ability to get better daughters from dams producing 9,000 pounds of milk, but in this class the normal expectation for improvement is high.

The showing of sire 6 when mated to cows having tested daughters sired by other bulls is interesting, and the results appear in Table 9.

TABLE 9.—*Comparison of the daughters of sire 6 with daughters of other sires from the same dams*

Sire No.	Milk production of—		Sire No.	Milk production of—		Sire No.	Milk production of—	
	Dam	Daughters		Dam	Daughters		Dam	Daughters
	Pounds	*Pounds*		*Pounds*	*Pounds*		*Pounds*	*Pounds*
6	21,331	12,183	6	10,784	11,334	6	8,903	10,443
20		16,618	12		13,346	4		11,961
4		13,049	6	10,428	12,797	6	8,420	8,588
6	13,437	16,701	4		13,199	12		10,678
4		19,387	6	9,569	13,033	4		10,351
12		19,108	12		10,641			
6	10,797	13,236	6	9,225	12,537			
12		11,074	12		11,691			

On the basis of his showing when in direct comparison with other sires, it would appear that sire 6 was rated too high by this system of ranking.

Two other sires had 5 of their 6 daughters better than the dams, but the small number of pairs in each case offers inadequate material for study. Sire 5 is one of these, and his 6 daughters show the greatest average increase over their dams. Among his daughters are 2 sets of full sisters—one of 3 and the other of 2. The variability even in these full-sister groups is great enough to make the high rank of this bull questionable. Sire 1 is the other bull with 5 of his 6 daughters better than their dams. He was mated to better average dams than sire 5, and his ability to improve production failed in only one instance, but that was when he was mated to a dam in the 10,000-pound class (where the whole population of sires raised 58 per cent of their daughters above their dams), and in this case the daughter produced 163 pounds less than her dam.

Eight of ten daughters by sire 16 exceeded their dams in milk production. He was mated to nine dams that were below the average in milk production, and his daughter from the best dam was inferior to her dam and was the poorest of her three maternal half sisters. This bull's progeny performed in close approximation to the average for the population, and his apparent ability to sire daughters better than their dams may be accounted for by the fact that he was bred to the class of dams that on the average produce a high percentage of daughters with ability exceeding their own.

It would appear from these cases that while the ability of a sire, when used in herds representative of this population, to get a high percentage of daughters which exceed their dams in milk production, is worthy of notice, it is not a definite assurance that this sire is much above the average in his transmitting ability for milk production.

If a sire were mated only with low-producing dams, where the normal expectation is for a high percentage of daughters better than their dams, he would have to show an increase in this percentage in order to show better than average ability. It would be easier to judge of the relative ability of sires that were mated to dams of different levels of production.

SIRES WITH GREATEST PROPORTION OF DAUGHTERS POORER THAN THEIR DAMS

Three of the fifty-one sires had daughters all of which were below the dams in milk production. The daughters of sire 43 show the greatest average decline of the 51 groups. The number of daughters is only seven, but the results are so uniform as to warrant discussing them. The dams of these daughters constitute the highest-producing group of dams in this study. The general expectation is for daughters of high-producing dams to fall below their dams in production, but apparently this sire was an exceedingly poor transmitter of production or he would have maintained a higher level of milk yield in daughters from this grade of dams than he did. There is also a correlation between the records of these dams and their daughters of $+0.831 \pm 0.079$.

Sire 44 affords a similar example, as the group of dams with which he was mated ranked second in average milk production. His daughters were all inferior to their dams, and the correlation between dams and daughters is $+0.937 \pm 0.031$. This sire even failed to get improved daughters from two dams in the 10,000-pound class, a class in which the normal expectation for an increase is better than even.

The third bull whose daughters all produced less milk than their dams was sire 50. The average production of the dams to which he was mated was lower than that of the dams to which either sire 43 or 44 was mated.

Judging by the performance of the offspring of these three sires, it is evident that when a bull consistently sires daughters that are poorer producers than their dams, he carries few if any of the factors for high milk production, and that the producing ability of the offspring of such a sire will depend largely on what they inherit from the dams. This study also showed that sires 43, 44, and 50 sired daughters with the greatest decrease in milk production.

SIRES WITH DAUGHTERS SHOWING THE GREATEST AVERAGE INCREASE OVER THEIR DAMS

The three sires whose daughters show the highest average increase in milk yield over their dams, are Nos. 5, 2, and 3. Sire 5 has already been discussed. Sire 2 has 12 daughters that averaged 1,864 pounds of milk more than their dams, but this includes 1 that produced 8,952 pounds more than her dam. With this one exception sire 2 failed to accomplish much when mated to dams above the 12,000-pound class but showed unusual ability to increase the production from dams below that class. Considering only his 7 daughters from these lower-producing dams, the average increase in production by daughters over dams is more than 3,000 pounds, which is well above the general average increase from dams of this quality.

Sire 3 evidenced the same weakness as sire 2 on high-producing dams and the average increase in production by his daughters over their dams is due to the performance of his daughters from the lower-grade dams. Two sets of three full sisters contribute a large part toward establishing this high average increase.

The evidence offered by these three groups of daughters indicates that high increases in production by daughters over dams occur mostly where the dams rank in the lower levels of production. Bulls

selected on this basis alone would be those that have been mated with lower-producing cows.

The opposite is clearly indicated in the case of sires 43 and 44. Bulls that fail to sire improved daughters from low-record dams may safely be classed as the poorest sires for transmitting milk production.

A further illustration of this apparent effect of the average production of the dams on that of the daughters is shown by Table 10, which lists the 6 sires whose daughters showed the greatest average increase in production over that of their dams, and the 6 sires whose daughters showed the greatest average decrease in production. The 6 high-ranking sires were mated to groups of dams with an average rank of 33, and 39 of them were grade B dams and 19 grade A dams. The 6 low-ranking sires were bred to groups of dams whose average rank was 12, and 14 of them were grade B dams and 30 were grade A dams.

TABLE 10.—*The six best and six poorest sires, ranked according to the greatest average increase and decrease, respectively, in production of their daughters over the dams of the daughters*

Group and sire No.	Average increase (+) or decrease (−) (pounds) in milk production by daughters over dams	Rank of dams, on basis of milk production	Number of dams in—	
			Grade A	Grade B
Six best:				
5	+1,928	33	3	3
2	+1,864	27	6	6
3	+1,776	25	5	12
9	+1,767	49	0	7
16	+1,518	45	1	9
1	+1,505	19	4	2
Six poorest:				
43	−3,749	1	7	0
44	−3,185	2	5	2
50	−2,236	18	4	2
51	−2,104	24	4	3
48	−1,656	10	5	5
45	−1,343	16	5	2

SIRES WITH DAUGHTERS HAVING THE HIGHEST AVERAGE MILK PRODUCTION

The five sires (Nos. 10, 13, 8, 1, and 2), whose daughters are highest in average milk production include only one sire that was considered under the discussion of sires having daughters with a high average increase over dams. As already stated, only 5 of the 54 dams that produced over 15,000 pounds of milk dropped daughters that excelled them as producers, and 3 of these 5 daughters were by sires 1, 8, and 10.

Sire 10 has the distinction of siring the most uniformly good daughters, so far as milk production is concerned, of any of the 51 sires. The coefficient of variability for his 7 daughters is 15.23 ± 2.75. They averaged 14,994 pounds of milk; and each one produced more than 12,000 pounds, which is well above the average of all daughters. Five of the dams were also in the class above 12,000 pounds, and the other two were in the 9,000-pound class. His daughters from the last two were far ahead of their dams in milk production.

Sire 13 has 11 daughters that averaged 13,685 pounds of milk from dams that averaged 12,851 pounds. Only 6 exceeded their dams in

milk production, and there was wide variation in their records. His daughters from grade A dams are better than the average, but his best showing is in the daughters he sired from the lower-record dams. His record on this small group of daughters is not consistent.

Sire 8 has 13 daughters. They rank third in average milk production, but they show the greatest variability of any group of daughters. The dams also vary widely in their producing ability, but there is a correlation of -0.690 ± 0.098 between daughters and dams. The transmitting ability of this sire as shown by the performance of his daughters is rather unusual. The 4 best dams to which he was mated all had records above 12,000 pounds of milk, and the daughter of each of these cows was better than her dam. In the whole population only 1 daughter in 4 exceeded her dam when the dams produced 12,000 pounds or more of milk. The next 4 dams to which sire 8 was mated were all in the 11,000-pound class where the chances were even that a daughter would be a better or poorer producer than her dam, but all of the daughters fell below their dams and 3 of them by more than 1,000 pounds of milk. While such inconsistent performance is confusing, it is one of the things to be expected in analyzing material which is as heterozygous as this appears to be.

Sire 1 has 6 daughters with an average milk production of 13,482 pounds despite one with a production of only 8,652 pounds. Omitting this one, his showing is unusually good, both with respect to the high average increase in production by his daughters over their dams and the uniformity of the increase.

The daughters of sire 2 follow closely the general population. Three dams in the class above 13,000 pounds had daughters poorer than themselves. One dam in the 12,000-pound class dropped his highest-record daughter as well as one daughter in the 12,000-pound class. Mated to dams in the class below 12,000 pounds he got 7 daughters that were all decidedly better producers than their dams, but his breeding performance approaches the average in spite of the high production of his daughters and their high average increase over their dams.

SIRES WITH DAUGHTERS HAVING THE LOWEST AVERAGE MILK PRODUCTION

Daughters of sires 51, 47, and 32 have the lowest average milk production of all the daughter groups. Of seven daughters by sire 51 only one was above the average in production, and she came from a dam with a record of 14,657 pounds of milk. Only one daughter exceeded her dam, and she was from the poorest of the dams.

Sire 47 has only 1 daughter above the average in milk production and only 1 other that exceeds her dam. Of 12 daughters only 3 have records above 10,000 pounds of milk. Eight of the daughters were from dams in the 9,000 or 10,000 pound class, where the chances are 7 in 10 that the daughter will excel the dam, but only 2 out of these 8 daughters were better than their dams.

Sire 32 has 2 daughters with records above 12,000 pounds of milk, but the other 9 daughters were poor enough to pull the average of his daughters down to 9,688 pounds. The dams were all below average; and in the whole population the chances would be about 8 in 10 that daughters would excell these dams, but only 4 of his 11 daughters were better than their dams.

SIRES WITH LARGE GROUPS OF DAUGHTERS

Sires with large numbers of daughters usually afford more conclusive data for studies of this kind than sires with only a small number of daughters. Sire 11, with 48 daughters, has a larger number than any other. Table 11 shows the relative ability of the dams to which sire 11 was mated and of his daughters from those dams.

TABLE 11.—*Correlation surface of milk production of the 48 daughters of sire 11 and their dams; also average production of various groups of dams and daughters*

Milk-production class of dams [1]	Number of daughters in milk-production class [2] of—										Total daughters	Average milk production of—		Average increase (+) or decrease (−) by daughters over dams
	17,000 pounds	16,000 pounds	15,000 pounds	14,000 pounds	13,000 pounds	12,000 pounds	11,000 pounds	10,000 pounds	9,000 pounds	8,000 pounds		Dams	Daughters	
											Number	*Pounds*	*Pounds*	*Pounds*
21,000 pounds						1					1	21,324	12,554	−8,770
14,000 pounds	1	1	1	1	1						5	14,228	15,681	+1,453
13,000 pounds						1					1	13,507	12,004	−1,503
12,000 pounds			1	1	1	2	1	2			8	12,778	12,876	+98
11,000 pounds		1		1	1	1	1		1		6	11,661	13,027	+1,366
10,000 pounds				1	1	1			3	1	7	10,346	10,989	+643
9,000 pounds				1	3	2	4	1	1	2	14	9,660	11,575	+1,915
8,000 pounds					1		1	2	2		6	8,565	10,821	+2,256
Total	1	2	2	5	8	8	7	5	7	3	48	11,192	12,251	+1,059

[1] None of the dams, except the one in the 21,000-pound class, exceeded 14,000 pounds.
[2] None of the daughters was in a class above 17,000 pounds.

The daughters of sire 11 include a group of five full sisters from a cow with a 14,228-pound milk record. The unusually strong showing of this full-sister group plays a prominent part in bringing his rating as high as it is, and it may safely be said that their inheritance for milk production from the dam was better than from their sire. If these full sisters were omitted, it would reduce the average milk production of this sire's daughters by 400 pounds. When sire 11 was mated to other grades of dams the results were generally better than average, but not markedly so, particularly in the case of the dams in the 8,000 and 9,000 pound classes.

Sire 12 had the next largest number of daughters, a total of 38. His offspring from four dams with milk records over 15,000 pounds were all disappointing, but five of eight daughters were better than their dams that had records of 12,000 to 15,000 pounds, which is above the normal expectation. Twenty-two of the dams to which he was mated were in the class below 11,000 pounds, and his daughters from these dams averaged higher in production than the daughters of all the bulls, but there is nothing of distinguishing importance in his breeding record as a whole.

Two other sires, 27 and 36, had 30 or more daughters from tested dams. Sire 27 was mated to a group of dams that averaged about 11,000 pounds of milk, although more than half of them had records above that figure. His get from the better dams was disappointing; and while 12 of his 15 daughters from the poorer dams were better than their dams, the increase in production was below the normal

expectation. The dams of the daughters of sire 36 averaged 12,622 pounds of milk and varied widely in their individual production. Only 12 of the 30 daughters exceeded their dams in milk production, and 8 of these were from dams with records below 11,000 pounds. If sires 27 and 36 had been mated only with dams in the 8,000, 9,000, and 10,000 pound classes, each would have ranked high on a basis of percentage of daughters better than dams, and yet on mixed groups of dams they failed to maintain the average production.

These four sires follow more or less the trends of the whole sire population, which is to be expected, since their daughters constitute almost one-fourth of the total number of daughters. They offer some interesting contrasts, however, in average production of their daughters and in the percentage of superior daughters. The daughters of sire 36 averaged over 1,000 pounds of milk more than those of sire 27; yet the daughters of sire 36 averaged 816 pounds less than their dams.

Interpretation of these results requires some knowledge of what relationship exists between the producing ability and the transmitting ability of high-record and low-record cows.

Sire 40 affords another good example of a sire that showed ability to get better-producing daughters from low-record cows, but from dams in the class above 11,000 pounds the daughters were all inferior.

The analysis of the individual breeding records of the remaining bulls did not bring out any information of value from the standpoint of heredity except to emphasize that the bulls are mediocre in their ability to sire daughters with any degree of uniformity in their milk production.

FULL-SISTER GROUPS OF DAUGHTERS

Interesting groups of animals in studies of this kind are the full sisters. Because of the additional relationship on the maternal side, this group has a higher coefficient of correlation between dams and daughters than is true of the population as a whole. The actual figure is $+0.314 \pm 0.024$ as compared to $+0.262 \pm 0.015$ for the 611 pairs.

The data include 1 set of 5, 2 sets of 4, 17 sets of 3, and 58 pairs of full sisters, making a total of 180 daughters. The 78 dams involved have a weighted average of 11,392 pounds of milk, or 176 pounds below the average of all dams; and the 180 daughters averaged 11,757 pounds which is 25 pounds more than the average of all daughters. The 58 dams of pairs of sisters averaged 11,405 pounds of milk, and the 116 daughters averaged 11,719 pounds. The average difference between members of the pairs is 2,328 pounds of milk.

Of the 58 pairs of full sisters there are 22 in which both daughters exceeded the dam in milk production, 19 in which both produced less than the dam, and 17 in which one daughter produced more and one less than the dam. As would be expected, 16 of the 22 dams with both daughters better are grade B dams, and 13 of the 19 dams with both daughters inferior are grade A dams.

While the preceding analysis may indicate that full sisters tend to show a similar trend in their milk production, a closer analysis of the figures reveals wide discrepancies in the producing ability of sisters. Of the 22 pairs of sisters in which both are better than the dam, 11 show a difference of more than 1,000 pounds of milk between members of the pair. These differences range from 1,067 to 6,872 pounds. In

only 4 of the other 11 pairs are the members less than 500 pounds apart. The members of 14 of the 19 pairs in which both are poorer than the dam differ by more than 1,000 pounds, and the differences are as high as 4,360 pounds. Four of the remaining pairs differ by less than 500 pounds. The 17 pairs of sisters in which one is better and one poorer than the dam show even less similarity in production. None of them differ by less than 500 pounds, 15 differ by more than 1,000 pounds, and 5 by more than 6,000 pounds of milk.

To summarize briefly, in only 8 of the 58 pairs of full sisters are the members sufficiently alike to have milk-production records differing by less than 500 pounds; 10 differ by 500 to 1,000 pounds; 16 differ by 1,000 to 2,000 pounds; 8 by 2,000 to 3,000 pounds; 7 by 3,000 to 4,000 pounds; 3 by 4,000 to 5,000 pounds; and 6 by more than 6,000 pounds of milk. It would appear, therefore, that for animals of this relationship there is but 1 chance in 7 that sisters will differ from each other by less than 500 pounds of milk, and 1 chance in 10 that they will differ by more than 6,000 pounds in the year's production. The chances are somewhat better than even that the difference between sisters will be less than 2,000 pounds on the average.

The preceding statements are general, but specific instances of large and small differences between full sisters are given in Table 12.

TABLE 12.—*Extremes of likeness and variation in milk production of pairs of full sisters*

Sire No.	Milk production of—		Difference between daughters' records	Sire No.	Milk production of—		Difference between daughters' records
	Dam	Daughters			Dam	Daughters	
	Pounds	*Pounds*	*Pounds*		*Pounds*	*Pounds*	*Pounds*
33	18,188	10,340 9,957	383	9	10,859	18,188 9,892	8,296
36	14,456	14,314 9,954	4,360	35	10,135	9,204 9,064	140
12	14,412	19,448 13,444	6,004	39	10,100	10,382 10,116	266
2	12,344	21,296 12,187	9,109	16	9,348	18,233 11,361	6,872
12	11,681	16,115 9,270	6,845	9	8,938	9,755 9,503	252
36	11,160	9,662 9,658	4				

These few cases fail to exhaust the possibilities for analysis and study of this group of full sisters, as they afford many contrasts and contradictions. Here again is found evidence of heterozygosis or mixed inheritance in the animals studied. This appears to be applicable to both male and female. Sires 9 and 12 manifest this quality, and notable inconsistency is evident in the progeny of other sires studied.

In Table 13 some interesting combinations of sisters by the various sires are shown.

TABLE 13.—*Milk-production records of pairs of full sisters by various sires, and the records of the dams*

Sire No.	Milk production of—		Increase (+) or decrease (−) by daughters over dam	Sire No.	Milk production of—		Increase (+) or decrease (−) by daughters over dam
	Dam	Daughters			Dam	Daughters	
	Pounds	*Pounds*	*Pounds*		*Pounds*	*Pounds*	*Pounds*
11	11,673	16,435	+4,762	32	9,725	12,658	+2,933
		13,311	+1,638			8,929	−796
	11,581	14,921	+3,340		9,250	9,170	−80
		12,316	+735			7,745	−1,505
	10,287	9,612	−675		8,838	9,290	+452
		8,541	−1,746			8,753	−85
13	18,751	18,265	−486	36	14,456	14,314	−142
		15,414	−3,337			9,954	−4,502
	13,260	14,127	+867		12,690	12,115	−575
		13,338	+78			11,605	−1,085
	13,058	12,644	−414		11,160	9,662	−1,495
		10,897	−2,161			9,658	−1,502
	9,557	16,645	+7,088		10,084	10,562	+478
		14,277	+4,720			8,641	−1,443
14	10,862	11,501	+639		9,164	12,072	+2,908
		8,840	−2,022			9,502	+338
	10,823	11,914	+1,091	41	11,850	11,235	−611
		10,365	−458			8,073	−3,775
21	10,002	11,189	+1,187		11,393	12,304	+917
		10,311	+309			11,724	+331
	9,797	12,185	+2,388	46	12,531	12,833	+302
		8,210	−1,587			12,044	−487
27	11,215	11,025	−190		11,885	13,333	+1,448
		9,903	−1,312			8,385	−3,500
	9,036	13,538	+4,502				
		9,537	+501				
	8,957	9,561	+604				
		9,188	+231				

COMPARISON OF FULL SISTERS WITH THEIR DAMS

In 14 of the 58 full-sister pairs, one daughter's milk record is within less than 50 pounds of the dam's while that of the other daughter differs from that of the dam by more than 1,000 pounds.

The data show that the production of both members of 21 pairs of sisters differed from the dams by more than 1,000 pounds. In 9 of these 21 pairs both daughters were better than the dam, in 7 pairs both were inferior, and in the remaining 5 pairs, the record of 1 daughter was above, and that of the other was below her dam's record by more than 1,000 pounds.

There are 10 pairs of sisters of which both daughters have records that differ from the dam by less than 1,000 pounds. In 7 of the pairs, both daughters exceed the dam in production, and in 3 pairs 1 daughter is better, and the other poorer than the dam.

Seventeen dams gave birth to sets of three sisters. Table 14, showing the extremes of likeness and variability in milk production of these 17 sets, includes the set in which the daughters are the most alike in milk production and also the set in which they differ the most.

TABLE 14.—*Two sets of three full sisters, showing the extremes of likeness and difference in milk production of the 17 sets*

Sire No.	Milk production of—		Increase (+) or decrease (−) by daughters over dam
	Dam	Daughters	
	Pounds	*Pounds*	*Pounds*
3	11,452	15,919	+4,467
		10,559	−893
		7,858	−3,594
33	11,089	11,999	+910
		11,690	+601
		11,279	+190

The extreme differences in these sets of three full sisters range from 720 to 8,061 pounds of milk, with an average difference of 3,156 pounds, which is about 27 per cent of the 11,570-pound average milk production of the 51 daughters in the 17 sets.

In 5 of the sets all 3 daughters exceeded the dams, and in 2 sets all 3 were poorer producers than the dams. In each of 4 sets, 2 daughters were better than the dam, and 1 was poorer; while in each of the other 6 sets 1 daughter was better than the dam and 2 were poorer.

There are five sets in which one daughter differs from the dam by less than 500 pounds in milk production, while the record of her sisters both differ by more than 1,000 pounds from the dam's record.

The breeding inconsistency of some of the bulls is further emphasized by the results of these multiple matings.

The sets of 4 sisters are only 2 in number, and afford meager data for study. Both dams are in the 12,000-pound class, and in each set of daughters only 1 produced more than the dam while 3 produced less. This is 1 in 4 as compared with the ratio of 1 in 3 for all dams in the 12,000 pound-class.

One set of five sisters is interesting because of the uniform distribution of the daughters. Records of this group are shown in Table 15.

TABLE 15.—*Milk-production records of five full sisters by sire 11*

Milk production of—		Increase (+) or decrease (−) by daughters over dam	Difference in milk production between nearest daughters
Dam	Daughters		
Pounds	*Pounds*	*Pounds*	*Pounds*
	17,793	+3,565	1,131
	16,662	+2,434	975
14,228	15,687	+1,459	1,025
	14,662	+434	1,053
	13,609	−619	

MATERNAL HALF SISTERS

The groups of maternal half sisters form a class most frequently found among the higher-record dams. There is evidence here of the purpose of the breeders to mate the outstanding cows to different bulls, and also of their wish to test the daughters of great cows. Table 16 gives the results of mating three cows, having milk records above 20,000 pounds, to eight different bulls.

TABLE 16.—*Results of mating three cows in the 20,000-pound milk-production class to eight different bulls*

Milk production of—		Increase (+) or decrease (−) by daughters over dams	Sire No.	Milk production of—		Increase (+) or decrease (−) by daughters over dams	Sire No.	Milk production of—		Increase (+) or decrease (−) by daughters over dams	Sire No.
Dam	Daughters			Dam	Daughters			Dam	Daughters		
Pounds	*Pounds*	*Pounds*		*Pounds*	*Pounds*	*Pounds*		*Pounds*	*Pounds*	*Pounds*	
23,911	14,949	−8,962	44	21,331	16,618	−4,713	20	21,324	16,655	−4,669	36
	12,980	−10,931	19		13,049	−8,282	4		12,554	−8,770	11
	12,562	−11,349	35		12,183	−9,148	6				

On an average these eight daughters produced 8,353 pounds less milk than their dams, and it would seem that the breeders' quest for a nick failed utterly in these instances. Judged by the ranking of these eight sires, five were only of average ability and could hardly be classed as suitable mates for these good cows.

Table 17 shows two maternal half-sister combinations that are unusual.

TABLE 17.—*Unusual milk-producing ability in two sets of maternal half sisters*

Milk production of—		Increase (+) or decrease (−) by daughters over dams	Sire No.
Dam	Daughters		
Pounds	*Pounds*	*Pounds*	
17,010	21,928	+4,918	23
	12,014	−4,996	3
13,437	19,387	+5,950	4
	19,108	+5,671	12
	16,701	+3,264	6

In the first case, a dam with a record of 17,010 pounds of milk had daughters by sires 3 and 23. The production records of these daughters are contrary to what would be expected, as sire 3 has 17 daughters that averaged 13,240 pounds of milk, with 12 better than their dams, and sire 23 has 20 daughters that averaged 12,177 pounds, with 11 better than their dams.

In the second case, the ability of the dam to transmit production to all her daughters is shown by three half sisters sired by different bulls. This is a very unusual case, as it is rare indeed in this study that dams with records above the average have offspring that are uniformly better than themselves. This would appear to be a case of the female approaching homozygosity for a high level of milk production, for, while the sires of these daughters would be classed as good bulls, none of them showed the ability to get daughters which were uniformly better than their dams, and only 9 of 45 daughters from dams in the 13,000-pound class were better than their dams.

There are 34 pairs of maternal half sisters, and in 17 pairs both daughters were better than the dam, in 8 pairs both daughters pro-

duced less than the dam, and in 9 pairs one daughter was better and the other poorer than the dam. In a general way this would seem to indicate that the sires of these daughters were genetically superior to the dams, so far as milk production is concerned.

Five dams each produced a pair of sisters and a third daughter by a different bull. Their records are shown in Table 18.

TABLE 18.—*Comparison of two full sisters with a maternal half sister*

Milk production of—		Increase (+) or decrease (−) by daughters over dams	Sire No.	Milk production of—		Increase (+) or decrease (−) by daughters over dams	Sire No.
Dam	Daughters			Dam	Daughters		
Pounds	*Pounds*	*Pounds*		*Pounds*	*Pounds*	*Pounds*	
16,618	16,426	−192	26	10,135	11,289	+1,154	25
	14,782	−1,836	26		9,204	−931	35
	14,011	−2,607	12		9,064	−1,071	35
12,690	12,115	−575	36	10,084	14,597	+4,513	1
	11,605	−1,085	36		10,562	+478	36
	11,347	−1,343	15		8,641	−1,443	36
12,658	13,567	+909	23				
	13,302	+644	23				
	11,483	−1,175	16				

In each of the first three cases the full sisters were sired by a bull of lower rank than the other, but the half sister proved to be a poorer producer than either of the full sisters. In the other two cases there is a marked difference between the pairs of full sisters and the other daughter of each dam, but there is evidence of the influence of the sires, and the results are more according to expectations.

The data include six pairs of maternal half sisters in which the daughter of the higher-ranking sire is a markedly poorer producer than the other half sister.

Such evidence throws no light on the method of transmission of milk production other than to indicate the extremely heterozygous make-up for the hereditary factors determining level of production in the animals.

The cow's record is a fair measure of her own producing ability, but there is still much uncertainty as to what value this may have as an index of her transmitting ability. In general, there is a relationship between the record of the dam and the ability of the daughter, as it has already been demonstrated that a positive correlation exists between records of dams and daughters. However, individual exceptions are all too numerous, and in some cases this evidence is strengthened by results shown by the matings of different cows with the same bulls. The two dams listed in Table 19 have records which are approximately equal.

TABLE 19.—*Relation of dam's milk record to her transmitting ability*

Milk production—		Increase (+) or decrease (−) by daughters over dam	Sire No.
Dam	Daughters		
Pounds	*Pounds*	*Pounds*	
8,830	8,591	−239	12
	8,287	−543	20
8,696	17,685	+8,989	12
	14,900	+6,204	20

Both dams have daughters by the same two bulls of quite different rank, and the pairs of half sisters are strikingly different in their producing ability. Although in the entire population of daughters the chances were only 5 in 64 that the daughter of a cow in the 8,000-pound class would fall below her dam, yet here two daughters of an 8,000-pound dam, sired by different bulls, both failed to equal the dam's record. The same two bulls sired daughters from another cow in this class both of which far exceeded their dam in production of milk. While these two cows showed equal ability to produce milk, there is incontrovertible evidence that they varied greatly in transmitting production to their daughters.

SIGNIFICANCE OF CORRELATION COEFFICIENTS OF MILK PRODUCTION OF DAMS AND DAUGHTERS

Statistical constants for groups of daughters of different sires are shown in Table 8. Because of the small numbers involved, the majority of the correlation coefficients are not significant, but even where the correlations are high and the errors small there is no evidence that the correlation coefficient throws any light on the relative value of the various bulls. This may be due to the fact that it is derived from production records which may or may not be an indication of transmitting ability. Positive correlations are more numerous than are negative correlations, but this is to be expected where the entire population of dams and daughters are positively correlated. The correlations range from $+0.937 \pm 0.031$ for daughters of sire 44, to -0.727 ± 0.129 for daughters of sire 29, showing almost the limits of spread. There is no evidence that this constant has any bearing on the rank of the bull as herein determined. This is indicated in Table 20, for the 11 sires with the largest coefficients of correlation. This table also shows the relationship to the average production of the dams. There is better correlation between the dams of high-average production and their daughters than between dams of low-average production and their daughters.

TABLE 20.—*Relation of correlation coefficients of milk production of dams and daughters to rank of sire and to rank of dams in average production*

Rank of sire	Daughter-dam pairs	Correlation coefficients of milk production of dams and daughters	Average milk production of dams per year	Rank of dams
	Number		*Pounds*	
44	7	+0.937±0.031	14,118	2
43	7	+.831±.078	15,279	1
1	6	+.750±.120	11,977	19
10	7	+.729±.119	13,518	4
8	13	+.690±.098	12,082	15
31	9	+.581±.148	10,049	47
26	6	+.572±.185	12,780	8
29	6	−.727±.129	10,916	39
38	6	−.715±.224	10,103	46
33	14	−.611±.112	12,366	12
14	7	−.575±.170	9,964	48

Variability has no significance in these small groups of dams and daughters. In 29 of 51 cases the daughters had a higher coefficient of variability than their dams. Since average milk production by daughters is one basis on which the bulls were ranked, it is natural that the daughters of the higher-ranking bulls with their greater average production should show more variability.

INFLUENCE OF MILK RECORD OF SIRE'S DAM

It has long been a practice of breeders in selecting herd sires to emphasize the milk and butterfat records of the dam, and many of the bulls used in the better herds are the sons of high-record cows. The official milk records of the dams of 30 of the bulls in this analysis are shown in Table 8. The importance which is attached to the dam's record is shown by the fact that 5 of the 30 bulls had dams with milk records above 20,000 pounds.

The 30 tested dams ranged from 21,733 to 8,853 pounds in milk production and averaged 14,042 pounds, 19 of them producing more than 12,000 pounds. There is such a wide difference between the better and poorer dams that an analysis of the 30 sires as a class would be of doubtful significance. These sires, mated to cows that averaged 11,797 pounds of milk, sired 316 daughters that averaged 11,948 pounds; while the 21 bulls from untested dams, mated to cows that averaged 11,324 pounds, got 295 daughters that averaged 11,500 pounds of milk (increases of 151 and 176 pounds, respectively). Although these sons of tested dams were mated with better cows they failed to get as large an average increase in production as did the other 21 bulls. In each group 53 per cent of the daughters excelled their dams. There is not such a close parallel in the case of daughters that averaged over 12,000 pounds of milk, as the 30 sires (sons of record dams) sired 141, or 58.5 per cent, of the 241 daughters with a milk production above that figure. Table 21 shows the number of daughters of each milk-production class sired by the two groups of bulls.

TABLE 21.—*Number of daughters in various milk-production classes sired by two groups of bulls*

Milk-production class	Daughters sired by 30 sons of tested dams	Daughters sired by 21 sons of untested dams	Milk-production class	Daughters sired by 30 sons of tested dams	Daughters sired by 21 sons of untested dams	Milk-production class	Daughters sired by 30 sons of tested dams	Daughters sired by 21 sons of untested dams
Pounds	*Number*	*Number*	*Pounds*	*Number*	*Number*	*Pounds*	*Number*	*Number*
24,000	----------	1	17,000	4	5	10,000	41	44
23,000	1	----------	16,000	7	5	9,000	57	57
22,000	----------	----------	15,000	7	14	8,000	19	34
21,000	2	----------	14,000	27	15	7,000	2	5
20,000	----------	1	13,000	36	19			
19,000	4	2	12,000	51	35	Total	316	295
18,000	2	3	11,000	56	55			

For a further study of the sons of tested cows the 30 bulls were divided into two lots, 19 from dams with records above 12,000 pounds of milk being in one lot, and 11 from dams with records below that figure in the other lot. If the record of the dam of the sire is significant, it might be of interest to know how many daughters of these sires equaled or excelled the milk record of their paternal granddams. The first five sires from dams with records over 20,000 pounds of milk failed to get a single daughter whose record was equal to that of her paternal granddam. Considering the sires in the first lot, it is found that only 32 of their 190 daughters produced more than the paternal granddam. If all 30 sires are considered, then 99 of the 316 daughters excelled the dams of their sires, but a number of these dams were only fair producers.

Perhaps a more severe test for the sire would be the performance record of his daughters that are from dams equal to, or better than his own dam. The 19 sires from the higher-record dams were mated to 36 cows that were as good or better producers than the dams of these sires, and only 3 of the 36 daughters are better producers than their dams and paternal granddams. By including the sons of the lower-record cows there are 27 of 74 daughters ahead of both dam and sire's dam. Two-thirds of the daughters of these sires, from dams with records below the sires' dams, are better producers than their dams. It would seem that a bull's reputation as a sire able to increase production could best be enhanced by mating him to cows inferior to his own dam as producers. Of course, this is more or less indicated in the material previously studied.

The sires whose dams had records of over 12,000 pounds of milk sired 190 daughters that averaged 12,374 pounds of milk from dams that averaged 12,303 pounds, and only 99 exceeded their dams. This increase of 71 pounds in milk is 201 pounds less than the increase shown by the 126 daughters of the other sires from tested dams. The 126 daughters averaged 11,306 pounds of milk and their dams 11,034 pounds. The sons of the higher-record cows were mated to dams that were far better than the dams to which the sons of lower-record cows were mated, and the average increase of the daughters of the latter bulls was greater than the normal expectation from dams of this class. Had the dams to which both lots of bulls were mated been of equal producing ability, no doubt the 19 sires would have shown the greater increases.

A fair way to make an estimate of the significance of the record of the sire's dam would be to determine what each group of sires accomplished when mated with dams of various levels of production. In Table 22 are shown the results of mating three groups of sires to dams with milk records of 9,000, 10,000, 11,000 and 12,000 pounds respectively.

TABLE 22.—*Comparative results of mating sires in three different groups with cows in four milk-production classes*

Sire group	Daughter-dam pairs	Milk production of—		Increase (+) or decrease (−) in milk yield by daughters over dams	Daughters with records —	
		Dams	Daughters		Above dams	Below dams
COWS IN 9,000-POUND MILK-PRODUCTION CLASS						
	Number	*Pounds*	*Pounds*	*Pounds*	*Number*	*Number*
19 sires from dams above 12,000 pounds	23	9,447	12,653	+3,206	21	2
11 sires from dams below 12,000 pounds	29	9,620	11,514	+1,894	25	4
21 sires from untested dams	63	9,470	10,884	+1,414	46	17
All sires	115	9,503	11,315	+1,812	92	23
COWS IN 10,000-POUND MILK-PRODUCTION CLASS						
19 sires from dams above 12,000 pounds	33	10,536	11,823	+1,287	20	13
11 sires from dams below 12,000 pounds	27	10,485	10,605	+120	13	14
21 sires from untested dams	54	10,466	11,336	+870	33	21
All sires	114	10,491	11,304	+813	66	48

TABLE 22.—*Comparative results of mating sires in three different groups with cows in four milk-production classes*—Continued

COWS IN 11,000-POUND MILK-PRODUCTION CLASS

Sire group	Daughter-dam pairs	Milk production of—		Increase (+) or decrease (−) in milk yield by daughters over dams	Daughters with records —	
		Dams	Daughters		Above dams	Below dams
	Number	*Pounds*	*Pounds*	*Pounds*	*Number*	*Number*
19 sires from dams above 12,000 pounds	38	11,424	11,830	+406	24	14
11 sires from dams below 12,000 pounds	27	11,595	11,524	−71	13	14
21 sires from untested dams	56	11,455	11,328	−127	22	34
All sires	121	11,477	11,530	+53	45	62

COWS IN 13,000-POUND MILK-PRODUCTION CLASS

19 sires from dams above 12,000 pounds	20	12,521	12,883	+362	10	10
11 sires from dams below 12,000 pounds	18	12,526	11,539	−987	4	14
21 sires from untested dams	30	12,456	11,308	−1,148	9	21
All sires	68	12,495	11,832	−663	23	45

ALL COWS

19 sires from dams above 12,000 pounds	190	12,303	11,797	−506	90	91
11 sires from dams below 12,000 pounds	126	11,034	11,306	+272	70	56
21 sires from untested dams	295	11,324	11,500	+276	157	138
All sires	611	11,568	11,732	+164	326	285

The sires from dams with milk records over 12,000 pounds have daughters in every class that are of higher average production than their dams. The increase was invariably larger than that shown by the other two groups of sires. Without exception they also had a larger percentage of daughters that exceeded their dams.

While the untested dams of the 21 sires in the group under discussion may only have lacked the opportunity to make an official record, it is conceivable that these sires might have entered either of the other classes if their dams had been tested. And yet the results as shown in Table 22 lead to the conclusion that the milk record of the dam of a sire affords some indication of his transmitting ability. This is best borne out where the record of the dam is above 12,000 pounds, and the cows to which the bull is mated are neither extremely low nor high producers.

HALF SISTERS OF THE SIRES

Twenty-one of the bulls in this analysis are sons of other sires in this study. A comparison of the daughters of a bull with his own paternal half-sisters is given in Table 23 for these sires.

TABLE 23.—*Average yearly milk production of the daughters and half sisters of 21 sires*

Rank of sires's sire	Rank of sire	Average milk production of—			Rank of sire's sire	Rank of sire	Average milk production of—		
		Sire's daughters	Sire's half sisters	Dams of sire's half sisters			Sire's daughters	Sire's half sisters	Dams of sire's half sisters
		Pounds	*Pounds*	*Pounds*			*Pounds*	*Pounds*	*Pounds*
2	19	13,238	13,268	11,404	12	26	13,257	12,404	11,329
3	43	11,530	13,240	11,464	16	46	10,851	11,774	10,256
4	5	13,108	12,952	11,793	20	10	14,994	11,981	11,392
	18	12,516			22	38	10,505	12,196	11,040
	24	11,989			35	44	10,933	11,089	11,768
	29	10,933			36	1	13,482	11,806	12,622
	30	12,849			39	14	11,096	10,176	11,012
7	49	9,736	12,996	11,958	40	37	10,916	9,965	11,058
8	21	10,902	13,495	12,082					
11	15	11,489	12,251	11,192					
	23	12,177							
	33	11,205							
	41	10,507							

On the basis used for ranking sires there are only 4 in 21 cases where the son ranks higher than his sire. Seventeen of the bulls are sons of sires that rank in the upper half, which indicates some appreciation of the worth of the sires in the choice of their sons for herd bulls. Sire 4 had five sons and sire 11 had four sons, but all fell below their sires' rank. Here is further evidence of the heterozygous genetic make-up of these animals as shown by a tendency to revert to the breed average as has already been found true on the female side.

The best-bred sire undoubtedly is sire 19. He is by sire 2, whose 12 daughters averaged 13,268 pounds of milk, or 1,864 pounds more than their dams, and 8 of the 12 exceeded their dams in milk production. The dam of sire 19 has a record of 21,733 pounds of milk for a year. His own 11 daughters averaged 13,238 pounds, with a range only from 10,485 to 15,317 pounds, but their dams averaged 13,550 pounds and only 6 of the 11 daughters exceeded their dams. The interesting point in this bull's record is that his daughters from dams with records below 13,000 pounds were all better than the dams, while his daughters from dams with records above 13,000 pounds were inferior. From the five high-record dams that averaged 18,503 pounds he got daughters that averaged 13,288 pounds, and from the 6 other dams that averaged 11,089 pounds, he got daughters that averaged 13,197 pounds. Had he been used only on dams of the latter class, he would have reached a high rank as a sire of daughters of high milk production.

Another sire with indications of good breeding was No. 43, a son of sire 3, from a dam with a record of 12,583 pounds. His sire had 17 daughters that averaged 13,240 pounds of milk, or 1,776 pounds more than their dams, 12 being better. Sire 43 has already been discussed, as he was mated to 7 dams that averaged 15,279 pounds, and all of his daughters fell below their dams in milk production, the average decrease being 3,749 pounds. This performance record of his daughters indicates that he did not inherit the factors for the high level of milk production possessed by his sire and his dam.

Sire 5 was the highest ranking son of sire 4, but his dam produced only 9,569 pounds of milk, which was the lowest record of any of the dams of the sons of sire 4. The 13 daughters of sire 4 averaged 12,952

pounds of milk or 1,159 pounds more than their dams, while the 6 daughters of sire 5 averaged 13,108 pounds and exceeded their dams by 1,928 pounds. The dam of sire 5 evidently transmitted better producing ability than her own as indicated by her 9,569-pound record, which is what may be expected in a heterozygous population.

Sire 18, another son of sire 4, was from a dam that produced 14,412 pounds of milk. His 14 daughters averaged 12,516 pounds of milk. or 213 pounds more than their dams, and 9 were better than their dams. The two best dams to which sire 18 was mated produced over 23,000 and 16,000 pounds of milk, respectively, and their daughters made records 9,000 and 6,000 pounds lower. When these two dam-and-daughter pairs are dropped from consideration, the remaining dams average 11,051 pounds of milk, and their daughters 12,665 pounds. This is an increase of 1,614 pounds by the daughters over their dams, which would have raised his ranking materially.

Sire 24, the next ranking son of sire 4, was from a dam that produced 12,571 pounds of milk. His tested daughters number only six, and in this small group he shows ability to transmit only a fair level of production, just about maintaining the dams' average of 11,970 pounds.

Sire 29, also a son of sire 4, was from a cow with a record of 11,505 pounds of milk. The six dams to which he was mated averaged 10,916 pounds of milk, and he raised this average through his daughters by only 17 pounds. The breeding record of this sire is far below that of his own sire, as his paternal half sisters average more than 2,000 pounds of milk more than his daughters.

Sire 30 is the lowest ranking son of sire 4, although his dam produced 13,750 pounds of milk. He was a bull with a very good pedigree, and when mated to six cows that averaged 12,814 pounds of milk, he produced only two daughters that excelled their dams. His dam was a daughter of sire 22, and while her own record is 13,750 pounds, her dam produced 18,110 pounds, or 4,360 pounds more.

None of these five sons of sire 4 ranked as high as he, and the only one whose daughters averaged higher than his half sisters was from the poorest dam of the lot.

Sire 49, one of the poorest in this study, is a son of sire 7. His dam produced 11,920 pounds of milk, but when he was mated to eight cows that averaged 10,731 pounds, he got eight daughters that averaged 9,736 pounds of milk. His seven half sisters averaged close to 13,000 pounds.

Sire 21 was a son of sire 8, whose 13 daughters averaged 13,495 pounds of milk. His dam had a yearly record of 11,212 pounds, but his 11 daughters averaged only 10,902 pounds, or less than his own dam and his half sisters.

Sire 11 had four sons, all of which ranked lower than their sire. The highest of the four was sire 15, whose dam had a yearly record of 12,324 pounds. Since he was the son of a bull whose 48 daughters averaged 12,251 pounds of milk, and from a dam with more than 21,000 pounds, his breeding would indicate that he had possibilities to sire increased production, yet his 10 daughters averaged only only 11,489 pounds of milk from dams that averaged 10,664 pounds.

155872°—33——3

They averaged about 10,000 pounds less in milk production than their paternal granddam, and midway between their own dams and the half sisters of their sire.

The next ranking son of sire 11 was sire 23, whose dam produced 14,227 pounds of milk. This bull was mated to 20 cows that averaged 12,352 pounds of milk, or considerably more than those bred to sire 15. His 20 daughters averaged slightly less than their dams in milk production, but 11 of the 20 excelled their dams. Although only one of his daughters was better than his dam in milk production, his 20 daughters averaged close to his 48 half sisters.

The third ranking son of sire 11 was sire 33, whose dam yielded 13,506 pounds of milk. He was mated to 14 cows that averaged 12,366 pounds of milk and got 14 daughters that averaged only 11,205 pounds; none of the daughters equaled the record of his dam.

The fourth ranking son of sire 11 ranked forty-first in this study. His dam produced 10,681 pounds of milk in a year, and his nine daughters averaged 10,507 pounds from dams that averaged 11,418 pounds.

A point of interest about these four sons of sire 11 is that they rank in the same order as the milk records of their dams.

Sire 10 offers the best illustration of improved transmitting ability. His sire was No. 20, whose dam had a yearly record of 21,023 pounds. The daughters of sire 20 averaged 11,981 pounds of milk and were from dams that averaged 11,392 pounds. Sire 10 was from a dam with a production of 21,331 pounds, and his seven daughters averaged 14,994 pounds from dams that averaged 13,518 pounds. These daughters have the highest average milk production of all the 51 daughter groups in this study, and the bull shows exceptional ability in raising the production of daughters from dams of this grade. There may be evidence here that he inherited and transmitted the producing ability of his own dam and the dam of his sire. Although neither bull sired daughters as good as his own dam the level of production was raised by both sires.

Sire 44 was the son of a poor sire, and of a dam that produced 13,896 pounds of milk in a year. His sire, No. 35, had 15 daughters that averaged 11,089 pounds of milk from dams that averaged 11,768 pounds. Even with this good dam sire 44 mated to cows that averaged 14,118 pounds of milk had seven daughters that averaged 10 933 pounds, a decrease of 3,185 pounds of milk.

By way of contrast, sire 1 was a son of sire 36 and out of a dam with a record of 17,793 pounds. The 30 daughters of sire 36 averaged 11,806 pounds of milk from dams with an average production of 12,622 pounds. Although sire 1 had a low-ranking sire, his dam was a good daughter of sire 11 and exceeded her dam in milk production by by 3,565 pounds. The six daughters of sire 1 averaged 13,482 pounds of milk, and it would appear that his ability to sire daughters that were better producers than their dams was the result of a combination of good factors inherited from his low-ranking sire and from his better-bred dam.

Sire 14 was a son of sire 39 and out of a dam with a milk record of 8,853 pounds. Although poorly bred he sired daughters that averaged 11,096 pounds of milk when mated to seven dams that averaged less than 10,000 pounds.

From the evidence offered by these cases it would appear that a sire's transmitting ability may be inherited from either or both his sire and his dam, but that the inheritance for milk production, so far as the observations on this population indicate, is still so mixed that results are uncertain even where careful selection based on performance of the parents is practiced.

The daughters of only 6 of the 21 bulls exceeded their sire's half sisters in average milk production, 3 others were close, but 12 groups of daughters were decidedly below their sires' half sisters.

METHODS OF MATING

Only 3 of the 51 bulls in this analysis show more than remote common ancestry, and there is not sufficient material to make comparisons on a basis of inbreeding, linebreeding, or outbreeding. This may be due to lack of popularity of systems of close mating or the practice of using imported bulls on home-bred cows.

Fifteen sires with a total of 306 daughters have only 6 linebred and 3 inbred daughters.

COMBINATIONS OF SIRES IN RELATION TO THEIR INFLUENCE ON MILK PRODUCTION

There are some interesting combinations in the get of several sires which are presented for whatever they may be worth.

Sire 23 had a total of 20 daughters, 11 of which excelled their dams in milk production. The daughters averaged 12,177 pounds of milk yearly, and their dams 12,352 pounds. Four of these dams were by sire 8, and nine were by sire 16. The dams by sire 8 averaged 14,285 pounds of milk, and their daughters by sire 23 averaged 14,825 pounds. The dams by sire 16 averaged 11,819 pounds of milk, and their daughters by sire 23 averaged 11,424 pounds. The daughters from the better grandsire easily excelled those descended from the lower-ranking grandsire.

Another similar example showing the influence of a good bull carrying through to the second generation is found in the record of sire 36. He had 30 daughters, and the dams of half of them were by sire 11, the dams of the other half being by various bulls. The dams by sire 11 averaged 12,479 pounds of milk and their 15 daughters by sire 36 averaged 12,493 pounds, an increase of 14 pounds, with 8 daughters exceeding their dams in production. The other dams, by various sires, averaged 12,766 pounds of milk, and their 15 daughters by sire 36 averaged 11,120 pounds, a decrease of 1,646 pounds, with 11 daughters producing less than their dams. Although sire 36 ranked low as a sire of daughters of higher milk production, only 12 of his daughters being better than their dams, 8 of these were from dams by sire 11, which is a good indication that they carried more factors for high production than did the other dams with which sire 36 was mated.

Sire 27 holds a medium rank, and three of his five highest ranking daughters and his poorest daughter are from dams which are half sisters. Five of these half-sister dams averaged 9,913 pounds of milk, and their daughters by sire 27 averaged 12,269 pounds. On the other hand, three daughters of sire 50 that averaged 10,768 pounds of milk had daughters by sire 27 that averaged only 9,994 pounds of milk.

The record of sire 12 is good on all groups of dams and may be summarized as follows:

Four dams by sire 4 averaged 10,677 pounds of milk and their daughters averaged 11,014 pounds.

Six dams by sire 6 averaged 10,996 pounds of milk and their daughters averaged 12,011 pounds.

Eight dams by sire 22 averaged 12,404 pounds of milk and their daughters averaged 11,538 pounds.

Three dams by sire 40 averaged 9,810 pounds of milk and their daughters averaged 11,819 pounds.

Four dams by one bull averaged 11,095 pounds of milk and their daughters averaged 13,888 pounds.

Thirteen dams by various bulls averaged 11,445 pounds of milk and their daughters averaged 13,223 pounds.

This bull failed to maintain production when mated to the better daughters of sire 22, but his get from the poorer daughters of sires

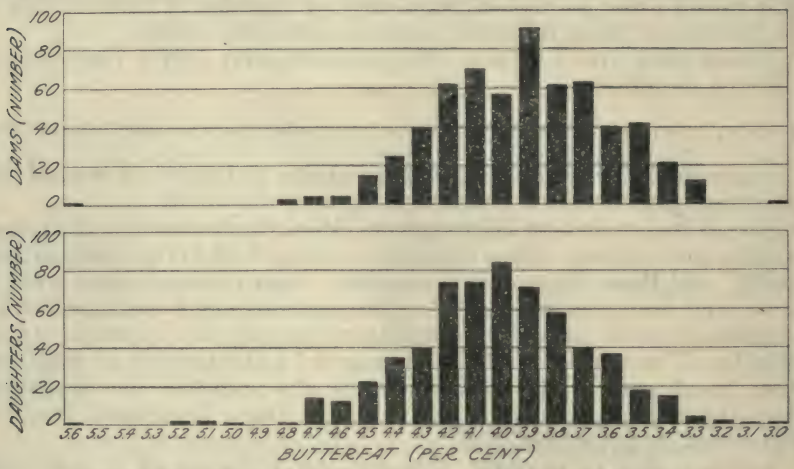


FIGURE 6.—Distribution of dams and daughters, according to their butterfat test

4, 6, 22, and 40, in most cases, excelled their dams in milk production.

Five daughters of one sire not listed in this study were the dams of 18 daughters by sire 11. The weighted average of the dams was 12,453 pounds of milk, and the daughters averaged 13,810 pounds, 13 exceeding their dams. Sire 47 was a half brother to these dams and 6 of his daughters when bred to sire 11 had daughters that averaged 10,636 pounds of milk, or 306 pounds more than their dams. Aside from the 5 daughters of one cow, this sire also showed unusual ability to increase production from the lower-record daughters of other sires.

In studying this 2-generation relationship the point previously brought out is again emphasized, that bulls in this study make their best showing as sires of daughters of increased production when mated to the lower-record daughters of other good sires and usually their poorest showing when bred to the higher-record daughters.

ANALYSIS OF RECORDS OF BUTTERFAT TEST

Because percentage of butterfat is inherited independently, this characteristic will be discussed without consideration of the quantity of milk produced. Although there is a slight decline in the average percentage of butterfat with advancing age, the change is not suffi-

ciently great to warrant the use of correction factors, and the actual figures are used without regard to the age at which the cow was tested.

The dams average 3.97 per cent butterfat in their milk while their 611 daughters average 4.07 per cent, an increase by the daughters of 0.10 per cent; 372, or 60.9 per cent, of the daughters had a higher average butterfat test than their dams. The coefficient of correlation was found to be $+0.257 \pm 0.026$, indicating a positive relationship between daughters and dams about the same as for milk yield.

The distribution of these daughters and dams, according to their butterfat test, is given in Table 24 and illustrated by Figure 6.

TABLE 24.—*Correlation surface of 611 Ayrshire daughters and dams, according to their butterfat test*

Butterfat test of dams [1]	Number of daughters whose butterfat test is—[2]																										Total
	5.6	5.2	5.1	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2	3.1	3.0	
5.6							1																		1
4.8	1									1															2
4.7						1		1		1			1												4
4.6			1							1	1	1													4
4.5							1			1	1	3	2	4	1	1				1					15
4.4							1		2	2	3	4	1	3	3	1		2	2	1					25
4.3			1				2	1	2	5	4	4	5	4	5	2	3	1	1						40
4.2							1	2	3	4	5	3	9	11	6	7	3	5	1	1	1				62
4.1				1			3	2	6	3	6	13	7	8	6	6	3	2	1	3					70
4.0								1	1	5	5	8	8	6	7	7	4	3	1	1					57
3.9							2	3	3	4	5	16	9	14	14	8	6	3	2	1				1	91
3.8								1	2	5	2	5	10	12	4	6	5	3	3	3			1		62
3.7		1							2	1	2	6	10	10	7	8	7	5		2	2				63
3.6		1					2			1	3	5	6	4	3	2	5	5	2		1				40
3.5							1	2	1		1	4	4	4	8	3	4	6		1		2			41
3.4									1	1	2	2	2	1	2	5		1	3	1					21
3.3														3	5	2		1	1						12
3.0																			1						1
Total	1	2	2	1		1	14	13	23	35	40	74	74	84	71	58	40	37	18	15	4	2	1	1	611

[1] None of the dams except the one with a butterfat test of 5.6 per cent exceeded 4.8 per cent.
[2] None of the daughters except the one with a butterfat test of 5.6 per cent exceeded 5.2 per cent.

The difference between dams and daughters, when measured in percentage of the dams' average, is greater in the average butterfat test than in milk yield, but a point of greater significance is that more than 60 per cent of the daughters had a higher test than their dams, thus showing a decided trend toward a better average test. With a significant majority of the daughters better than their dams in butterfat test there would seem to be evidence that the sires were exerting a favorable influence on this characteristic. This is further indicated by the fact that the average butterfat test of the daughters of 37 of the 51 sires is better than that of their dams.

A study of Table 25 reveals that the group of dams with a butterfat test of 4.14 per cent is the highest-testing group having a majority of daughters with a higher test than their own. Of 70 daughters in this group, 37 excelled their dams. In all lower-testing groups of dams a decided majority of the daughters are better than the dams, and in the largest single class (those testing 3.90 to 3.99) two-thirds of the daughters have a higher test than their dams. The table as a whole shows the tendency of daughters of extremely high and low testing dams to drift toward the breed average, somewhat the same as in the case of milk production, but in butterfat test the average in the second generation is appreciably higher than in the first generation.

TABLE 25.—*Average butterfat test of the 611 dams and daughters in the various grades*

Daughter-dam pairs (number)	Average butterfat test of—		Increase (+) or decrease (−) in test by daughters over dams	Daughters whose butterfat test is—		
	Dams	Daughters		Above dams		Below dams
	Per cent	*Per cent*	*Per cent*	*Number*	*Per cent*	*Number*
1	5.66	4.77	−0.89	0	0	1
2	4.81	5.04	+.23	1	50	1
4	4.74	4.53	−.21	1	25	3
4	4.65	4.56	−.09	1	25	3
15	4.54	4.12	−.42	1	7	14
25	4.43	4.10	−.33	5	20	20
40	4.34	4.20	−.14	13	33	27
62	4.24	4.07	−.17	17	27	45
70	4.14	4.14	0	37	53	33
57	4.04	4.07	+.03	32	56	25
91	3.95	4.10	+.15	61	67	30
62	3.84	4.01	+.17	43	69	19
63	3.75	3.99	+.24	54	86	9
40	3.63	4.03	+.40	35	88	5
41	3.55	3.96	+.41	38	93	3
21	3.44	3.97	+.53	20	95	1
12	3.35	3.89	+.54	12	100	0
1	3.00	3.52	+.52	1	100	0
Total or average	3.974	4.069	+.10	372	61	239

For convenience in discussion, the dams whose butterfat test is higher than the 3.974 per cent average will hereafter be referred to as the grade A dams, and those below the average will be called grade B dams. Similarly the daughters whose butterfat test is higher than the 4.069 per cent average will be referred to as the grade A daughters, and those below the average will be called the grade B daughters.

Accordingly, there are 318 grade A dams and 293 grade B dams, a more even division than in the case of milk production (p. 4.) The grade A dams dropped 168 of the 297 grade A daughters. In other words, while the grade A dams constitute only 52 per cent of the total number of dams, they bore 56 per cent of the grade A daughters. The grade A dams had an average butterfat test of 4.21 per cent, and their daughters averaged 4.13 per cent. The decrease of 0.08 per cent is slight, and 41.5 per cent of these daughters had a higher test than their dams.

The grade B dams had an average butterfat test of 3.72 per cent, while their daughters average 4.01 per cent, and 82 per cent of the daughters had a higher test than their dams. This difference of 0.29 per cent is about three times as great as the difference between the entire group of dams and daughters and shows the trend toward higher average tests.

In this random breeding, 6 of 10 daughters exceeded their dams in butterfat test, and if the dam tested above the average there were about 4 chances in 10 that her daughter would test higher; but if the dam tested below average, then more than 8 in 10 daughters were better.

It is apparent that breeding the higher-testing cows results in a somewhat higher average test in the daughters than does breeding the lower-testing dams, yet the difference between the two groups of daughters is 0.12 per cent while the dams differed by 0.49 per cent

on the average. This is very similar to the results shown in the case of milk production and emphasizes the need for greater care in the selection of sires. While there is noticeable average improvement and a majority of the daughters are better, the possibilities for surer and more pronounced increases in the percentage of butterfat through the selection of sires of better transmitting ability offer an interesting field for study.

GROUPS OF SIRES WITH DAUGHTERS HAVING HIGHEST AVERAGE BUTTERFAT TEST AND HIGHEST AVERAGE INCREASE IN TEST OVER DAMS

TEN SIRES WITH DAUGHTERS HAVING HIGHEST AVERAGE BUTTERFAT TEST

By selecting the 10 sires whose daughters have the highest average butterfat test, it is found that these sires were mated with cows whose average butterfat test was 3.99 per cent. These cows produced 120 daughters with an average test of 4.28 per cent, an increase of 0.29 per cent. While the butterfat test of these dams was about the same as that of the whole group of dams the increase shown by their daughters was nearly three times as large as the increase by the entire 611 daughters. Ninety-eight of the 120 daughters had a higher test than their dams.

The average results of the matings of these 10 bulls with dams of various classes are shown in Table 26.

TABLE 26.—*Average butterfat test of the daughters of 10 sires mated to dams of various grades*

Daughter-dam pairs (number)	Average butterfat test of—		Increase (+) or decrease (−) in test by daughters over dams	Daughters whose butterfat test is—		
	Dams	Daughters		Above dams		Below dams
	Per cent	*Per cent*	*Per cent*	*Number*	*Per cent*	*Number*
1	5.66	4.77	−0.89	0	0	1
2	4.81	5.04	+.23	1	50	1
2	4.73	4.39	−.34	0	0	2
1	4.61	5.17	+.56	1	100	0
1	4.51	4.74	+.23	1	100	0
2	4.45	4.49	+.05	1	50	1
8	4.32	4.42	+.10	4	50	4
11	4.24	4.34	+.10	7	64	4
14	4.14	4.35	+.21	12	86	2
12	4.04	4.17	+.13	9	75	3
16	3.95	4.22	+.27	15	94	1
15	3.85	4.13	+.28	13	87	2
13	3.75	4.15	+.40	12	92	1
12	3.62	4.31	+.69	12	100	0
8	3.56	4.19	+.63	8	100	0
1	3.45	4.19	+.73	1	100	0
1	3.36	4.01	+.64	1	100	0
Total or average	3.99	4.28	+.29	98	82	22

In this herd of 120 dams there are 57 grade A and 63 grade B dams. The grade A dams have an average test of 4.25 per cent, and their daughters by the 10 selected sires have an average test of 4.38 per cent, an increase of 0.13 per cent; whereas the 51 sires mated to 318 grade A dams had daughters that tested 4.13 per cent. Of these 57 daughters, 39 had a higher test than their dams. This is 68.4 per cent as against 41.5 per cent for the entire above-average group.

These same 10 sires, mated to 63 grade B dams with an average test of 3.75 per cent, produced daughters with an average test of 4.18 per cent, an increase of 0.43 per cent, or a 0.14 per cent greater increase than that shown by the 293 daughters of all the sires. Fifty-nine of the 63 had a higher test than their dams.

The comparative influence of the two groups of sires on the butterfat test of their daughters from two classes of dams is shown in Table 27.

TABLE 27.—*Comparative results showing the influence of two groups of sires on the butterfat test of their daughters from two classes of dams*

Number and grade of dams with which each group of sires was mated	Average butterfat test of—		Increase (+) or decrease (−) by daughters over dams
	Dams	Daughters	
51 sires:	*Per cent*	*Per cent*	*Per cent*
611 grade A and B dams	3.97	4.07	+0.10
318 grade A dams	4.21	4.13	−.08
293 grade B dams	3.72	4.01	+.29
10 best sires, selected on the basis of the highest average butterfat test of their daughters:			
120 grade A and B dams	3.99	4.28	+.29
57 grade A dams	4.25	4.38	+.13
63 grade B dams	3.75	4.18	+.43

The point of interest in these data is the strong indication of what could be accomplished toward improvement of the butterfat percentage by the use of sires such as those in this group of 10. When mated to the group of 120 representative dams, they sired daughters which exceeded their dams by about three times the average increase, and when the dams are divided into classes above and below average, the daughters of each class are decidedly better than the general run of daughters from these two grades of dams.

TEN SIRES WITH DAUGHTERS HAVING HIGHEST AVERAGE INCREASE IN BUTTERFAT TEST

Ten sires whose daughters showed the highest average increase in butterfat percentage were studied as a group. While the 130 daughters of these sires averaged 0.37 per cent higher in butterfat percentage than did their dams, and 115 of them were better than their dams, the dams averaged only 3.82 per cent in butterfat percentage and are not so representative of the whole herd of dams as those mated to the 10 sires previously discussed. Only 33 dams had a test above the general average of 3.974 per cent, and their average test was 4.26 per cent as compared to an average of 4.41 per cent for their daughters. The other 97 dams, with an average test of 3.68 per cent, had daughters with an average test of 4.11 per cent.

Those sires whose daughters show the greatest average increases in butterfat percentage over dams are usually found to have been mated largely with cows testing below the average, and the data as a whole indicate that increases from lower-testing dams are more frequent than decreases even when no sire selection is made.

INDIVIDUAL SIRES IN RELATION TO BUTTERFAT TEST OF THEIR DAUGHTERS

Table 28 shows the distribution of the daughters of the individual sires according to their percentage of butterfat. It also gives the average of the daughter group of each sire, the group averages of the dams, average differences, rank of each group, and number of daughters better than their dams.

Table 29 shows the means, the standard deviations, the coefficients of variability, and the coefficients of correlation for the average percentage of butterfat for the daughters of each sire and their dams.

TABLE 28.—*Distribution and rank of the daughters of each sire, according to their butterfat test, and number of daughters that tested better than their dams*

Rank of sire[2]	Number of daughters whose butterfat test is—[1]																							Total daughters	Average butterfat test of daughters	Rank of daughters according to butterfat test	Average butterfat test of dams	Rank of dams according to butterfat test	Increase (+) or decrease (−) by daughters over dams	Rank of daughters according to increase or decrease	Daughters making—	
	5.6	5.2	5.1	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2	3.1	3.0								Increase	Decrease
																									Number	*Per cent*		*Per cent*		*Per cent*		*Number*	*Number*
1								1				2			2	1									6	4.14	16½	4.09	13	+0.05	30½	4	2
2								1	1	2	1		1	1	3	1			1						12	4.16	13	4.08	16	+.08	24½	6	6
3							1			1		1	1	4	2	4	1	2							17	4.00	35	3.80	46	+.20	13	11	6
4		1					2		2		2		3	1		1	1								13	4.36	3	3.74	47	+.62	1	12	1
5																2	1	3							6	3.75	49	3.91	36	−.16	45	2	4
6											2	1	2	4	1	1	3								14	4.04	31	3.83	41	+.21	12	10	4
7												1		1	3	1			1						7	3.93	41	3.82	43	+.11	20½	5	2
8											1	1	1	1	2	2	1	2	2						13	3.88	42	3.85	39½	+.03	33½	7	6
9												4	1					2							7	4.04	31	3.96	32	+.08	24½	6	1
10												1			2	1	1	1	1	1					7	3.74	50	4.19	5	−.45	50	0	7
11		1					1	2	3	4	4	13	2	4	5	4	3			2					48	4.18	11½	3.99	28½	+.19	14	37	11
12				1			1	1	2	2	1	5	3	6	4	2	4	2	1	2		1			38	4.05	27½	3.98	30½	+.07	27	19	19
13											1	1	2			2	1	3			1				11	3.87	43	3.81	45	+.06	29	6	5
14											2	1	1	1					2						7	4.04	31	3.89	37	+.15	18	5	2
15							1	2		1			1	2	1	2									10	4.19	9½	4.02	25	+.17	16½	7	3
16											1			2	1	3					1		1	1	10	3.73	51	4.02	25	−.29	48	2	8
17											2	2	2		1	2									9	4.02	34	4.08	16	−.06	40	5	4
18							1	1	2		1	1			2	2	2								14	4.06	25	4.05	21	+.01	35½	7	7
19					1			1	1	1	2		3			1				1					11	4.18	11½	4.09	13	+.09	23	7	4
20								1	3	1			1						1	1					10	4.15	14½	4.12	9	+.03	33½	7	3
21										1			1	4	1	3		1							11	3.99	36½	3.82	43	+.17	16½	9	2
22							1				2		1		1	3	1	2	2	2	1				16	3.81	46	3.93	35	−.12	43	5	11
23							1	1	1	2	1	4	3	4	2		1								20	4.21	8	3.95	33½	+.26	10	19	1
24			1							1		1	3												6	4.37	2	4.26	3	+.11	20½	4	2
25								1	1	4	1	1	1	2	1		1								13	4.27	5	4.05	21	+.22	11	10	3
26												1	2	1	1	1									6	4.06	25	4.38	1	−.32	49	0	6
27	1						1	2	1	5	3	7	5	2	3					1					31	4.30	4	3.95	33½	+.35	5	26	5
28							1			1		1	4	2	3			1							13	4.12	19	4.08	16	+.04	32	7	6
29										1		1	1	1	2										6	4.11	20½	4.04	23	+.07	27	3	3
30												1	1	1	2	1									6	4.05	27½	4.16	6½	−.11	42	0	6
31											1	1	2	2	2					1					9	4.04	31	3.61	50	+.43	2	8	1
32									1	1		1	4	1		1	2								11	4.10	22	3.68	48	+.42	3	11	0
33											1	3		2	4	2		2							14	3.99	36½	3.65	49	+.34	6	13	1
34											1			1	3		1	2	1						9	3.86	44	4.11	10½	−.25	47	1	8
35								1	1	2		3	2		2	4									15	4.07	23	4.06	19	+.01	35½	9	6
36							1			2	2	3	6	7	1	1		4	1	2					30	3.96	39	4.11	10½	−.15	44	10	20

37								1	1	1		1		2	1		1	1							9	4.15	14½	3.85	39½	+.30	7½	7	2
38										1				1	2	1			1						6	3.95	40	3.98	30½	-.03	37½	3	3
39												1	3	1				1	1	1		1			9	3.84	45	3.57	51	+.27	9	7	2
40									1		2	1	2	2	2		1								11	4.13	18	4.01	27	+.12	19	7	4
41									2		2	1	1			1		1	1						9	4.14	16½	4.09	13	+.05	30½	6	3
42														2	1	2	2	1		1	1				10	3.77	48	4.23	4	-.46	51	0	10
43			1				2					2	1		1										7	4.45	1	4.15	8	+.30	7½	5	2
44							2				1		1	1		1	1								7	4.23	6½	3.87	38	+.36	4	7	0
45										1	3	1	1			1									7	4.23	6½	4.05	21	+.18	15	5	2
46													2	3		1		1							7	3.97	38	4.16	6½	-.19	46	2	5
47									1	1	1	1	1	3	2	2									12	4.11	20½	4.02	25	+.09	22	7	5
48												1		1	1	1	1	3	2						10	3.78	47	3.82	43	-.04	39	6	4
49												2	3	1		1	1								8	4.06	25	3.99	28½	+.07	27	5	3
50							1					1	2		1	1									6	4.19	9½	4.29	2	-.10	41	3	3
51											1	1	1	1	1	1	1								7	4.04	31	4.07	18	-.03	37½	2	5

[1] Except the 1 daughter whose butterfat test was 5.6 per cent, none exceeded 5.2 per cent.

[2] This rank is arrived at by combining the relative standings of these sires on milk production, butterfat production, increase in milk and butterfat production by daughters over dams, and proportion of daughters better than dams in milk and butterfat production.

TABLE 29.—*Rank of sire and of sire's sire, butterfat test of sire's dam, and statistical constants on the butterfat test of the daughters of the individual sires and of the dams of the daughters*

Rank of sire [1]	Butterfat test of sire's dam	Rank of sire's sire [1]	Daughters	Butterfat test of daughters			Butterfat test of dams			Correlation coefficient
				Mean	Standard deviation	Coefficient of variability	Mean	Standard deviation	Coefficient of variability	
	Per cent		*Number*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
1	3.79	36	6	4.14±0.07	0.24±0.05	5.91±1.15	4.09±0.05	0.17±0.03	4.05±0.79	+0.095±0.273
2	3.79		12	4.16± .06	.32± .04	7.72±1.06	4.08± .08	.39± .05	9.65±1.33	+.604± .124
3			17	4.00± .04	.27± .03	6.81± .79	3.80± .05	.28± .03	7.43± .86	+.194± .157
4	4.53		13	4.36± .07	.39± .05	8.86±1.17	3.74± .06	.30± .04	8.11±1.07	+.114± .185
5	3.65	4	6	3.75± .02	.07± .01	1.94± .38	3.91± .06	.22± .04	5.66±1.10	−.013± .275
6			14	4.04± .04	.20± .03	5.02± .64	3.83± .03	.19± .02	4.87± .62	−.243± .120
7			7	3.93± .06	.22± .04	5.54±1.00	3.82± .07	.27± .05	7.02±1.27	+.130± .251
8			13	3.88± .05	.24± .03	6.30± .83	3.85± .05	.25± .03	6.43± .85	+.103± .185
9	3.71		7	4.04± .07	.26± .05	6.45±1.16	3.96± .05	.22± .04	5.43± .98	+.343± .225
10	4.23	20	7	3.74± .06	.24± .04	6.32±1.14	4.19± .08	.31± .06	7.38±1.33	+.146± .250
11	4.15		48	4.18± .03	.32± .02	7.68± .53	3.99± .03	.23± .02	5.73± .39	+.231± .092
12			38	4.05± .04	.38± .03	9.34± .72	3.98± .04	.35± .03	8.79± .68	+.241± .103
13	3.91		11	3.87± .06	.28± .04	7.34±1.06	3.81± .06	.31± .04	8.10±1.16	+.240± .192
14	4.39	39	7	4.04± .09	.34± .06	8.33±1.50	3.89± .08	.33± .06	8.35±1.51	+.413± .211
15	3.61	11	10	4.19± .06	.30± .04	7.04±1.06	4.02± .04	.18± .03	4.36± .66	+.491± .162
16			10	3.73± .08	.38± .06	10.40±1.57	4.02± .06	.26± .04	6.47± .98	+.544± .150
17			9	4.02± .04	.19± .03	4.73± .75	4.08± .04	.18± .03	4.33± .69	+.648± .130
18	3.93	4	14	4.06± .06	.33± .04	8.06±1.03	4.05± .04	.23± .04	5.74± .73	−.525± .131
19	3.99	2	11	4.18± .08	.37± .05	8.93±1.28	4.09± .07	.37± .05	9.00±1.29	+.421± .167
20	3.83		10	4.15± .08	.37± .06	8.83±1.33	4.12± .04	.17± .03	4.21± .63	+.251± .200
21	4.04	8	11	3.99± .04	.18± .03	4.44± .064	3.82± .04	.26± .05	6.84± .98	+.131± .200
22			16	3.81± .06	.35± .04	9.13±1.09	3.93± .04	.22± .03	5.67± .68	+.473± .139
23	4.26	11	20	4.21± .04	.24± .03	5.75± .61	3.95± .03	.20± .02	5.08± .54	+.410± .126
24	3.45	4	6	4.37± .07	.37± .07	8.45±1.65	4.26± .06	.36± .10	8.36±1.63	+.621± .169
25	3.99		13	4.27± .05	.26± .03	6.02± .80	4.05± .04	.19± .03	4.74± .63	+.299± .170
26	4.64	12	6	4.06± .04	.14± .03	3.47± .68	4.38± .06	.23± .05	5.30±1.03	+.955± .024
27			31	4.30± .04	.35± .03	8.19± .70	3.95± .04	.34± .03	8.55± .73	+.472± .094
28			13	4.12± .05	.25± .03	6.09± .81	4.08± .05	.28± .04	6.96± .92	+.385± .159
29	3.54	4	6	4.11± .05	.17± .03	4.23± .82	4.04± .08	.28± .06	7.01±1.36	+.374± .237
30	4.20	4	6	4.05± .04	.15± .03	3.77± .73	4.16± .03	.13± .02	3.00± .58	+.708± .137
31	4.30		9	4.04± .06	.25± .04	6.28±1.00	3.61± .03	.14± .02	3.91± .62	+.194± .216
32			11	4.10± .05	.24± .03	5.79± .83	3.68± .04	.19± .03	5.03± .72	+.457± .161
33	4.50	11	14	3.99± .04	.21± .03	5.28± .67	3.65± .05	.29± .04	7.92±1.01	+.479± .139
34			9	3.86± .05	.23± .04	5.90± .94	4.11± .07	.30± .05	7.37±1.17	+.583± .148
35			15	4.07± .05	.26± .03	6.50± .80	4.06± .05	.27± .03	6.54± .81	+.458± .138
36			30	3.96± .03	.28± .02	7.05± .61	4.11± .04	.30± .03	7.22± .63	+.104± .122
37	3.87	40	9	4.15± .07	.32± .05	7.68±1.22	3.85± .07	.33± .05	8.45±1.34	−.349± .198
38		22	6	3.95± .07	.26± .05	6.67±1.30	3.98± .10	.36± .07	9.06±1.76	+.201± .264

39			9	3.84± .08	.36± .06	9.35±1.49	3.57± .04	.16± .02	4.37± .70	+.270± .208
40			11	4.13± .04	.22± .03	5.32± .77	4.01± .03	.13± .02	3.14± .45	+.403± .170
41	3.79	11	9	4.14± .08	.35± .05	8.35±1.33	4.09± .05	.21± .05	5.07± .81	+.709± .112
42	3.43		10	3.77± .05	.23± .03	6.08± .92	4.23± .03	.12± .03	2.94± .44	−.487± .163
43	4.31	3	7	4.45± .10	.41± .07	9.15±1.65	4.15± .06	.25± .04	5.99±1.08	+.386± .217
44	4.33	35	7	4.23± .09	.37± .07	8.65±1.56	3.87± .08	.32± .06	8.21±1.48	+.747± .113
45			7	4.23± .05	.19± .03	4.47± .81	4.05± .03	.13± .02	3.19± .58	−.047± .254
46	393	16	7	3.97± .04	.15± .03	3.86± .70	4.16± .05	.18± .03	4.42± .80	−.613± .159
47			12	4.11± .04	.23± .03	5.45± .75	4.02± .07	.34± .05	8.52±1.17	+.315± .175
48			10	3.78± .05	.21± .03	5.65± .85	3.82± .06	.27± .04	7.08±1.07	+.349± .187
49	3.86	7	8	4.06± .04	.16± .03	3.98± .67	3.99± .04	.16± .03	4.02± .68	+.509± .177
50	4.19		6	4.19± .08	.30± .06	7.09±1.38	4.29± .18	.66± .13	15.36±2.99	+.896± .054
51			7	4.04± .05	.19± .03	4.58± .83	4.07± .06	.22± .04	5.35± .96	+.453± .203

[1] The individual sires are referred to by the same number as the number of their rank as given in Table 7.

The discussion of the individual sires is limited to those which appear to be of unusual or of special interest.

SIRES WITH DAUGHTERS HAVING HIGHEST AVERAGE BUTTERFAT TEST

The seven daughters of sire 43 have the highest average butterfat test (4.45) of the 51 groups but are quite variable and range from 5.15 to 3.93 per cent. Six are above the grand average, and five are better than their dams. While this bull sired daughters of high average butterfat test, the dams from which they came had an average test of 4.15 per cent and were well above the general average.

Sire 24 has six daughters that averaged 4.37 per cent, all of which are above the grand average, although two failed to test as high as their dams. This group of dams had an average test of 4.26 per cent, and ranked third in the 51 groups of dams.

Thirteen daughters of sire 4 have an average test of 4.36 per cent and vary from 5.22 to 3.77 per cent. Most of these are from low-testing dams, and all but one have a higher test than their dams. These daughters made the highest average increase in butterfat test over their dams, and only three of the dams are above the grand average. This sire shows marked ability to increase the average test, but whether or not he would do so well on higher-testing dams is open to question.

Sire 27 ranks well both in the high average test of his 31 daughters and in the increase in test by the daughters over their dams. The 31 dams are quite variable in butterfat test, ranging from 4.81 to 3.56 per cent, the average being 3.95 per cent, but 26 of the daughters have a higher test than their dams and the average is 0.35 per cent better than that of the dams. Four of the five daughters that had lower test than their dams were from dams with a test above 4.20 per cent, and without question the ability of this bull to increase the percentage of butterfat when mated to dams below this figure is remarkably uniform.

The daughters of sire 25 rank fifth among the daughter groups in average percentage of butterfat. Their average test was 4.27 per cent while that of their dams was 4.05 per cent. This was an unusually good group of dams as 11 of the 13 were better than the average and while this sire's daughters did not make so high an increase over their dams as did those in several other groups, a comparison of this bull's get with all the daughters from similar dams shows that he got higher increases in percentage of butterfat and improved a larger proportion of his daughters.

SIRES WITH DAUGHTERS HAVING GREATEST AVERAGE INCREASE IN BUTTERFAT TEST

Sires 4, 31, 32, 44, and 27 are the five ranking bulls on a basis of average increase in percentage of butterfat by daughters over dams. Sire 4 has already been discussed, and attention is called to the low-average test of 3.74 per cent for the dams to which he was mated. Even on these low-testing mates his performance was above the average for similar groups.

The outstanding features of the data on these five bulls are the low-average test of their mates and the high proportion of their daughters that excelled their dams. The data are given in Table 30.

TABLE 30.—*Analysis of the data of five sires whose daughters have greatest average increase in butterfat test over their dams*

Sire No.	Daughter-dam pairs	Average butterfat test of—		Average increase by daughters over dams	Daughters making—	
		Dams	Daughters		Increase	Decrease
	Number	*Per cent*	*Per cent*	*Per cent*	*Number*	*Number*
4	13	3.74	4.36	0.62	12	1
31	9	3.61	4.04	.43	8	1
32	11	3.68	4.10	.42	11	0
44	7	3.87	4.23	.36	7	0
27	31	3.95	4.30	.35	26	5
Total or average	71	3.82	4.24	.42	64	7

It would be unfair to compare the records of sires 31 and 32 with other bulls, because all the dams to which they were bred tested well below the average, and the increases shown by their daughters are about the same as those made by all daughters from similar dams. It would appear that the showing made by these bulls can be accounted for to a considerable extent by the grade of dams with which they were mated.

Sire 44 has only a small number of daughters, but the dams from which they come vary widely in butterfat test and the correlation between dams and daughters is $+0.747 \pm 0.113$, all the daughters having a higher test than do their dams. He shows by this small group of daughters that he transmits the ability to increase butterfat percentage when mated to dams of various grades.

SIRES WITH LARGEST PROPORTION OF DAUGHTERS HAVING A HIGHER BUTTERFAT TEST THAN THEIR DAMS

On a basis of the largest proportion of daughters having a higher butterfat test than their dams, the leading bulls are sires 32, 44, 23, 33, 4, 31, and 9. The first two bulls increased the butterfat test of all daughters, and the other five bulls increased the test of all but one. In every case the average test of the dams to which the bull was mated was below the grand average, and in most instances it would seem that the sire's high rank in this regard is the result of his being mated to low-testing cows, rather than to the presence of an unusual combination of factors that enable a sire to transmit to all daughters the ability to produce butterfat of higher test, irrespective of the test of their dams.

Sires 32 and 44 have already been discussed, and the record of sire 23 is worthy of comment. His mates had an average butterfat test of 3.95 per cent, ranging from 4.35 to 3.58. The butterfat test of the daughters varied from 4.71 to 3.78 per cent, the average being 4.21 per cent, and 19 of the 20 had a higher test than their dams. His daughters from all grades of dams equaled or excelled the general average of all daughters both in actual increase in the percentage of butterfat and in the proportion of daughters better than their dams.

A surer interpretation may be made of the inheritance of the butterfat test than of the inheritance of milk production because environment interferes less with the expression of the inherited butterfat test.

Sire 33, with 13 of his 14 daughters better than their dams, affords another example of a sire mated to low-testing cows. The dams averaged 3.65 per cent in butterfat with only two over 4 per cent, and the daughters averaged only 3.99 per cent as compared with the average of 4.07 per cent for the daughters of all sires. This sire's record, even on low-testing dams, only approximated the average record of sires studied.

SIRES MATED TO LOW-TESTING DAMS

In the group of sires whose daughters show the greatest average increase in butterfat test over that of their dams, and also in the group with the largest proportion of daughters better than dams, it has been shown that the mates of these bulls were among the lowest-testing group of dams. Of the five sires (Nos. 39, 31, 33, 32, and 4) that were bred to the lowest-testing dams, the performance of all but sire 39 has already been discussed. Sire 39, mated to the lowest-testing group of females, has seven daughters that are better and two that are poorer than their dams in butterfat percentage. These dams range from 3.85 to 3.38 per cent in butterfat test, and the data show that on a comparative basis the best showing made by this sire was through his daughters from the better dams. Seven of the dams had a butterfat test below 3.6 per cent, and in these matings he did not get as good results as did the 51 bulls as a whole. The daughters of sire 39 are extremely variable in butterfat test, ranging from 4.21 to 3.24 per cent, and the correlation between dams and daughters is not significant because of the high probable error. Theoretically, this sire, if he had transmitting ability equal to the average ability of the 51 sires, would have shown large increases in the test in his daughters; but although seven of the daughters exceeded their dams, it appears that he did not transmit a high enough average test to raise the test of his daughters as much as is expected from this grade of dams.

Most of the foregoing discussion has been of sires mated to dams of low-average production because the sires selected probably attained their distinction by virtue of the fact that they were mated to low-testing dams. Since this appears to be the case, it might be well to study some of the sires bred to high-average dams.

SIRES MATED TO HIGH-TESTING DAMS

Sires 26, 50, 24, 42, and 10 were bred to the five groups of dams that ranked highest in butterfat test. These bulls sired 35 daughters, and only 7 had a higher test than their dams. The dams had an average test of 4.26 per cent, or 0.29 per cent more than the average of the 611 dams in the study; whereas the 35 daughters had an average test of 3.99 per cent, or 0.08 per cent less than the average of the daughters of the 51 sires. If these high-testing dams were transmitting the factors for a high percentage of butterfat, the expectation would be that their daughters by five different sires would average better than the whole daughter population, yet only 14 daughters tested higher than 4.07 per cent, the average of the 611 daughters. On analyzing the records of these sires, it is found that they sired larger proportions of inferior daughters than did the average sire.

The five bulls whose daughters show the greatest average decrease in butterfat test below that of their dams are sires 42, 10, 26, 16, and

34. The first three are in the group of sires mated to high-testing dams.

Four of these sires (42, 10, 26, and 34) together with sire 30 make up the group of five having the highest proportion of daughters testing lower than their dams. All were mated with groups of high-testing dams, and the first four sired daughters that were all lower in butterfat test than the dams, while sire 34 had one daughter that tested 0.01 per cent higher than her dam and eight that tested lower than their dams.

This set of sires includes 3 that were among the 5 mated to the 5 highest testing groups of dams, but their daughters from dams of all grades did not equal the daughters of the 51 bulls in average test. From 38 dams with an average test of 4.21 per cent these sires had daughters with an average test of 3.87 per cent, a decrease of 0.34 per cent, and 37 daughters had a lower test than the dams.

SIRES WITH DAUGHTERS HAVING LOWEST AVERAGE BUTTERFAT TEST

It is interesting to know which bulls are responsible for the lower-testing daughters, and in Table 31 are listed the five sires whose daughters have the lowest average butterfat test.

TABLE 31.—*Analysis of data of five sires whose daughters have lowest average butterfat test of all daughter groups*

Sire No.	Daughter-dam pairs	Average butterfat test of—		Average decrease by daughters over dams	Daughters making—	
		Dams	Daughters		Increase	Decrease
	Number	*Per cent*	*Per cent*	*Per cent*	*Number*	*Number*
16	10	4.02	3.73	−0.29	2	8
10	7	4.19	3.74	−.45	0	7
5	6	3.91	3.75	−.16	2	4
42	10	4.23	3.77	−.46	0	10
48	10	3.82	3.78	−.04	6	4

While these sires are alike in that they have daughters with a low average butterfat test, they differ markedly in transmitting ability. Generally speaking, 2 were mated to dams with a high average test, 1 to dams with an intermediate test, and the other 2 to dams with a low average test. All the daughter groups averaged lower than the dams in butterfat test, but this difference diminished as the average of the dams declined. Only 10 of the 43 daughters had a higher test than their dams, and these were all by sires mated to the dams of lower average test. For purposes of interpretation, it would be desirable that there be some consistency in the breeding results, but apparently such is not the case, as the low-average daughters do not all come from either high or low average dams, and the results shown in Table 33 seem to indicate that both the sires and the dams are contributing to the hereditary make-up of the daughters for butterfat test.

BEST SIRES ON BASIS OF FIGURES RELATING TO PERCENTAGE OF BUTTERFAT ONLY

The method used for ranking sires considers milk and butterfat production, which places double emphasis on milk production. For this reason, two groups of sires are discussed that are ranked by using

only the figures for percentage of butterfat as a basis for the three considerations, that is, average test of daughters, increase of daughters over dams, and proportion of daughters better than their dams. The five high-ranking bulls on this basis are sires 4, 44, 27, 23, and 43, and the five low-ranking bulls on the same basis are sires 10, 42, 16, 34, and 5. Both groups are shown in Table 32.

TABLE 32.—*Analysis of data of five high-ranking and five low-ranking sires on basis of figures relating to percentage of butterfat only*

Rank and Sire No.	Daughters	Average butterfat test of—		Increase (+) or decrease (−) in butterfat test of daughters over dams	Daughters making—	
		Dams	Daughters		Increase	Decrease
Five high-ranking sires:	*Number*	*Per cent*	*Per cent*		*Number*	*Number*
4	13	3.74	4.36	+0.62	12	1
44	7	3.87	4.23	+.36	7	0
27	31	3.95	4.30	+.35	26	5
23	20	3.95	4.21	+.26	19	1
43	7	4.15	4.45	+.30	5	2
Total or average	78	3.93	4.30	+.37	69	9
Five low-ranking sires:						
5	6	3.91	3.75	−.16	2	4
34	9	4.11	3.86	−.25	1	8
16	10	4.02	3.73	−.29	2	8
42	10	4.23	3.77	−.46	0	10
10	7	4.19	3.74	−.45	0	7
Total or average	42	4.10	3.77	−.33	5	37

The mates of the five high-ranking sires had an average butterfat test of 3.93 per cent as compared with 4.10 per cent for the mates of the low-ranking bulls, but the increases and decreases are greater than the average from these classes of dams.

Sire 11 has 48 daughters that averaged 4.18 per cent in butterfat test from dams that averaged 3.99 per cent, and 37 tested higher than the dams. This is a record above the average in all respects.

SIGNIFICANCE OF CORRELATION COEFFICIENTS AND COEFFICIENTS OF VARIABILITY OF BUTTERFAT TEST OF DAMS AND DAUGHTERS

Correlation coefficients have been calculated for the daughter group of each sire and the dams of the daughters, but on account of the small numbers in many of the groups these figures are not significant. In the cases of those bulls with 20 or more daughters the coefficients of correlation do not vary greatly from that of the whole population. It may be a coincidence but it so happens that the highest coefficient of correlation ($+0.955 \pm 0.024$) is between the daughters of sire 26 and their dams, which have the highest average test for all groups of dams mated to any one sire. The second ranking correlation coefficient ($+0.896 \pm 0.054$) is between the daughters of sire 50 and their dams, which rank second in high average percentage of butterfat. A somewhat similar result was found in regard to positive correlations on average milk production. The 10 sires whose daughters have the highest coefficients of correlation with their dams in percentage of butterfat are listed in Table 33.

TABLE 33.—*The 10 sires whose daughters have highest coefficients of correlation with their dams on basis of butterfat test*

Sire No.	Coefficient of correlation	Average butterfat test of dams	Rank of dams	Average butterfat test of daughters	Rank of daughters
		Per cent		*Per cent*	
26	+0.955±0.024	4.38	1	4.06	25
50	+.896± .054	4.29	2	4.19	9½
44	+.747± .113	3.87	38	4.23	6½
41	+.709± .112	4.09	13	4.14	16½
30	+.708± .137	4.16	6½	4.05	27½
46	−.614± .159	4.16	6½	3.97	38
18	−.525± .131	4.05	21	4.06	25
42	−.487± .163	4.23	4	3.77	48
37	−.349± .198	3.85	39½	4.15	14½
6	−.243± .120	3.83	41	4.04	31

The daughters of sire 18 from his higher-testing mates dropped below those from his lower-testing mates, with the result that the averages for both the dams and the daughters are about the same.

The ability of a sire to transmit the factors for a definite percentage of butterfat to his daughters might possibly result in a decrease in the variability of those daughters. This would be true as homozygosity for a definite percentage of butterfat is approached and as the offspring become purer for this characteristic. Twenty-six of the sires have groups of daughters less variable than their dams. There is no significant difference in the variability of high or low testing groups of daughters and dams.

The five bulls whose daughters are least variable are sires 5, 26, 30, 46, and 49, and those whose daughters show the greatest variation are sires 12, 16, 22, 39, and 43. Data on both groups are presented in Table 34.

TABLE 34.—*Analysis of data of sires whose daughters show the least and the greatest variability in butterfat test*

Sire No.	Daughters	Coefficient of variability	Average butterfat test of—		Daughters making—	
			Dams	Daughters	Increase	Decrease
	Number		*Per cent*	*Per cent*	*Number*	*Number*
5	6	1.94±0.38	3.91	3.75	2	4
26	6	3.47± .68	4.38	4.06	0	6
30	6	3.77± .73	4.16	4.05	0	6
46	7	3.86± .70	4.16	3.97	2	5
49	8	3.98± .67	3.99	4.06	5	3
16	10	10.40±1.57	4.02	3.73	2	8
39	9	9.35±1.49	3.57	3.84	7	2
12	38	9.34± .72	3.98	4.05	19	19
43	7	9.15±1.65	4.15	4.45	5	2
22	16	9.13±1.09	3.93	3.81	5	11

According to the information shown in Table 34, the five sires with the most variable daughters are better as a class than the five with the least variable daughters, but this is not a safe generalization as the make-up of each set is quite heterogeneous. Apparently, the coefficient of variability of the daughters' percentage of butterfat is of no significance in determining the breeding value of a bull except to indicate those sires that may transmit the factors for the wider range of butterfat percentage.

FULL-SISTER GROUPS OF DAUGHTERS

The dams of 58 pairs of full sisters had an average butterfat test of 3.93 per cent and the 116 sisters an average of 4.04 per cent, an increase of 0.11 per cent. There were 29 pairs in which both daughters tested higher than the dam, 15 pairs in which both tested lower, and 14 pairs in which one daughter tested higher and the other lower than the dam. This proportion of daughters better than dams is approximately the same as for the whole dam and daughter population.

As to similarity of these full sisters it is found that four pairs varied by as little as 0.01 per cent in their butterfat test. The maximum variation was 1.11 per cent, the average variation was 0.33 per cent, and 33 pairs varied less than the average.

Seventeen sets of three full sisters are from dams with an average butterfat test of 3.81 per cent and the daughters averaged 4.10 per cent. The most uniform set were by sire 11, and they tested 4.21, 4.21 and 4.17 per cent respectively. Their dam's test was 3.97 per cent. The widest variation is found in the sisters by sire 4 from a dam testing 4.60 per cent. The daughters tested 5.22, 4.70, and 4.18 per cent respectively.

Table 35 gives the percentage of butterfat of two groups of four and one of five full sisters.

TABLE 35.—*Percentage of butterfat of three groups of full sisters*

Sire No.	Butterfat test of—		Sire No.	Butterfat test of—		Sire No.	Butterfat test of—	
	Dam	Daughters		Dam	Daughters		Dam	Daughters
	Per cent	*Per cent*		*Per cent*	*Per cent*		*Per cent*	*Per cent*
11	4.26	4.38 4.24 4.06 3.81 3.79	11	3.82	4.41 4.26 3.94 3.76	27	3.76	4.46 4.23 4.19 4.16

The coefficient of correlation between the percentage of butterfat of full sisters was found to be $+0.584 \pm 0.010$, with slightly less variability among the lower-testing sisters.

A noteworthy record of performance in siring full sisters that are better than their dams in butterfat test is that of sire 27 as shown in Table 36.

TABLE 36.—*Butterfat test of groups of full sisters by sire 27*

Butterfat test of—		Average butterfat test of daughters	Butterfat test of—		Average butterfat test of daughters
Dam	Daughters		Dam	Daughters	
Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
3.76	4.46 4.23 4.19 4.16	4.26	3.56	4.60 4.23 3.94	4.26
3.98	4.52 4.46 4.29 4.39	4.42	3.94	4.75 4.12	4.44
3.62	4.27 4.18	4.28	3.94	4.29 4.01	4.15

All 17 daughters of this sire have a higher test than their dams, and the average increase in test is greater than that shown by the whole daughter population.

INFLUENCE OF BUTTERFAT TEST OF SIRE'S DAM

The butterfat record of the dam has long been used as a basis for selecting a herd sire, and it is interesting to determine if there is any noticeable difference to be found in the offspring of sires whose dams have different percentages of butterfat in their milk.

The dams of 30 sires had official records, and the butterfat test of these dams ranged from 4.64 to 3.43 per cent, averaging just 4 per cent. These sires were mated to 316 cows that averaged 3.99 per cent butterfat, and their daughters averaged 4.11 per cent.

The other 21 sires from untested dams were bred to 295 cows that averaged 3.96 per cent butterfat, and their daughters averaged 4.02 per cent. The amount of increase is 0.06 per cent in favor of the sires from tested dams. It is possible, of course, that the untested dams of the 21 sires may be as good as, or better than, those of the other sires.

For further study, the sires from tested dams are divided according to the butterfat tests of their dams. Thirteen of these dams had a butterfat test above 4 per cent, and 17 below.

The major points of interest in studying the transmitting ability of these various classes of sires are the average butterfat test of their mates, the average test of their offspring, the increase or decrease in test by daughters over dams, and the percentage of daughters that test higher than their dams. These data are given in Table 37.

TABLE 37.—*Average butterfat test of daughters of different classes of sires and their dams*

Number and class of sires	Daughter-dam pairs	Average butterfat test of—		Increase in butterfat test by daughters	Daughters better than dam	Sires that—	
		Dams	Daughters			Raised average	Lowered average
	Number	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Number*	*Number*
21 sires from untested dams	295	3.96	4.02	0.06	56	13	8
13 sires from dams testing above 4 per cent	161	3.94	4.14	.20	73	9	4
17 sires from dams testing below 4 per cent	155	4.04	4.08	.04	65	14	3
Total or average	611	3.97	4.07	.10	61	36	15

Table 37 shows that the sons of the higher-testing dams got the greatest increase in the butterfat test of the daughters and also had the largest percentage of better daughters. This average increase is double that shown by the daughters of all sires and more than three times as great as that shown by the daughters of sires from untested dams.

A 2-generation study of inheritance of percentage of butterfat is possible in several cases, and the best of these is the group of sons of sire 4. This sire, whose dam had a butterfat test of 4.53 per cent, got 13 daughters with an average test of 4.36 per cent from dams that tested 3.74 per cent, and the increase of 0.62 per cent was the largest

average increase in butterfat test shown by any sire's daughters. Apparently this son of a high-testing dam transmitted that characteristic to his female progeny. He had five sons from tested dams, and Table 38 gives the data on these sons.

TABLE 38.—*Comparative results on sire 4 and his five sons, relative to their transmitting ability for percentage of butterfat*

Sire No.	Average butterfat test of sire's—			Increase (+) or decrease (−) in butterfat test of daughters over their dams	Number of daughters making—	
	Dam	Mates	Daughters		Increase	Decrease
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Number*	*Number*
4	4.53	3.74	4.36	+0.62	12	1
30	4.20	4.16	4.05	−.11	0	6
18	3.93	4.05	4.06	+.01	7	7
5	3.65	3.91	3.75	−.16	2	4
29	3.54	4.04	4.11	+.07	3	3
24	3.45	4.26	4.37	+.11	4	2
Total or average		4.08	4.06	−.02	16	22

The sons of sire 4 do not approach their sire in ability to increase the butterfat test, for their 38 daughters average less than the dams and 22 have a lower test than their dams. The mates of these sons had a considerably higher average test than the mates of sire 4, but the fact remains that their daughters which did show increases were almost all from dams testing below 4.2 per cent.

This group of five sires affords an example of how pedigree selection of herd sires sometimes fails in its purpose. Assuming that a breeder is looking for a young sire that will raise the average butterfat test in his herd, by sound planning he would want a son of sire 4, since this sire has shown that he transmits an increased butterfat test to his daughters, and besides, his own dam had a butterfat test of 4.53 per cent. Having decided on the sire of his herd bull, the breeder finds there are five young sons available, sires 5, 18, 24, 29, and 30, as listed here. By the logic of pedigree selection, the breeder would choose sire 30 because he has the highest-testing dam of any of the available bulls. The dam of sire 30 tested 4.20 per cent, the half sisters averaged 4.36 per cent, and the paternal granddam 4.53 per cent, and yet when this bull was mated to cows whose average test was 4.16 per cent, he sired daughters that averaged 4.05 per cent, or 0.11 per cent less than their dams, and every daughter fell below her dam. On the other hand, sire 24 from the lowest-testing dam of any of the five sons, was mated to dams whose average test was 4.26 per cent and had six daughters which averaged 4.37 per cent, or 0.11 per cent higher than their dams, and four were better than their dams. The daughters of sire 18 just about equaled their dams in butterfat test; those of sire 5 fell below their dams; and although the daughters of sire 29 averaged 0.07 per cent higher than their dams, half of them tested lower. These results again point to the heterozygous condition of the animals in this study for percentage of butterfat as well as milk production.

Sire 11 had four sons from tested dams. The dam of sire 11 tested 4.15 per cent, and his 48 daughters from dams that tested 3.99 per cent averaged 4.18 per cent, 37 of the daughters exceeding their dams. The data on the four sons are presented in Table 39.

TABLE 39.—*Comparative results on sire 11 and his four sons, relative to their transmitting ability for percentage of butterfat*

Sire No.	Average butterfat test of sire's—			Increase in butterfat test of daughters over their dams	Number of daughters making—	
	Dam	Mates	Daughters		Increase	Decrease
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Number*	*Number*
11	4.15	3.99	4.18	0.19	37	11
33	4.50	3.65	3.99	.34	13	1
23	4.26	3.95	4.21	.26	19	1
40	3.79	4.09	4.14	.05	7	4
15	3.61	4.02	4.19	.17	7	3
Total or average		3.90	4.13	.23	46	9

Two of the sons of sire 11 (Nos. 33 and 23) had 34 daughters, 32 of which tested higher than their dams, but neither group of daughters averaged so high as the dam of their sire. The other two sons were out of lower-testing dams, and 14 of their 21 daughters tested higher than their dams and both daughter groups averaged higher than the dams of their sires. These sons collectively make an unusual showing in their ability to increase the average percentage of butterfat, and their daughters from all grades of dams are almost uniformly better than the average.

SIRES THAT INCREASED BOTH QUANTITY OF MILK AND PERCENTAGE OF BUTTERFAT

As the data on the 51 sires from the standpoint of their ability to transmit the factors for milk production and percentage of butterfat have already been discussed separately, there remains for consideration those sires that have the ability to increase both these characteristics in their offspring. Although many breeders may not feel deeply concerned about improving the percentage of butterfat and would rather concentrate their efforts toward raising the quantity of milk per cow, there is reason to believe that sires can be found which have the factors for increasing both the quantity of milk and the percentage of butterfat.

On a basis of averages, 19 sires raised both the quantity of milk and the percentage of butterfat, 9 raised the quantity of milk and lowered the percentage of butterfat, 17 decreased the quantity of milk and increased the percentage of butterfat, and the other 6 lowered both.

The sires that increased both the average milk production and the percentage of butterfat sired 261, or 42.7 per cent, of all the daughters in this study, but they had 117, or 61 per cent of the 192 daughters which exceeded their dams both in quantity of production and percentages of butterfat, and only 29, or 28 per cent, of the 104 daughters that were lower than their dams in both quantity and percentage.

The sires that lowered both the milk production and the percentage of butterfat had only 11 per cent of the total number of daughters and only 5, or less than 2 per cent, of the group that increased both milk production and butterfat percentage, and 30, or 29 per cent, of the 104 which dropped below dams in both milk production and butterfat percentage.

The averages of dams to which these four different classes of bulls were mated and the averages of their daughters are presented in Table 40.

TABLE 40.—*Average increase or decrease in milk and butterfat production, and in butterfat test by daughters of different groups of sires over the dams of the daughters*

Sire group	Milk production of—		Increase (+) or decrease (−) in milk production	Butterfat production of—		Increase (+) or decrease (−) in butterfat production	Butterfat [1] test of—		Increase (+) or decrease (−) in butterfat test
	Dams	Daughters		Dams	Daughters		Dams	Daughters	
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Per cent*	*Per cent*	*Per cent*
19 sires, increased both milk yield and butterfat percentage	11,296	12,310	+1,014	448	502	+54	3.94	4.09	+0.15
9 sires, increased milk yield and decreased butterfat percentage	11,151	12,417	+1,266	454	469	+15	4.06	3.87	−.19
17 sires, decreased milk yield and increased butterfat percentage	11,769	10,993	−776	464	460	−4	3.95	4.16	+.21
6 sires, decreased both milk yield and butterfat percentage	12,446	11,167	−1,279	510	436	−74	4.10	3.94	−.16

[1] Average of the butterfat tests of all cows in each group.

When measured in terms of total butterfat yield, the difference between the end groups is striking, as an increase of 54 pounds was made by daughters of the 19 bulls as against a decrease of 74 pounds for the get of the 6, but there is only a difference of 66 pounds between the averages of the two groups of daughters, and a disparity almost equally as great between the averages of the dams to which these bulls were mated.

Analyses of individual bulls on a basis of the records in increasing or decreasing both the quantity of milk and the percentage of butterfat would result in much repetition of what had already been written, but one of the outstanding sires in this respect is sire 4. Mated to 13 dams that averaged 11,793 pounds of milk testing 3.74 per cent butterfat, he increased milk production by 1,159 pounds and the butterfat test by 0.62 per cent in his daughters. Eight were better in both milk yield and butterfat test, and all but one tested higher than their dams. This unusual showing stamps this bull as prepotent for both increased milk yield and butterfat percentage and gives him first rank on average increase in quantity of butterfat.

Another good bull on this combined basis is sire 6 with 10 of his 14 daughters higher in both milk yield and percentage of butterfat. One of his failures is the daughter of a cow with a yearly record of more than 21,000 pounds of milk.

A very good showing was made by sire 11, 27 of his 48 daughters being better in both respects than their dams.

Of the six poor bulls, sire 51 decreased the milk yield of 6 of his 7 daughters and lowered the average 2,104 pounds, and 5 of his daughters tested lower than their dams for an average decrease in butterfat of 86 pounds.

Most of the other individual sires show the contradictory up and down results which are characteristic of the heterozygous material in this study.

INDEPENDENT INHERITANCE OF QUANTITY OF MILK AND PERCENTAGE OF BUTTERFAT

Further evidence of the independent inheritance of the factors for milk production and those for percentage of butterfat in the milk is afforded by this study. In 25 of the 51 dam-and-daughter groups the quantity of milk and percentage of butterfat went together, either up or down, while in the remaining 26 groups the quantity of milk was increased and the percentage of butterfat lowered, or vice versa.

A study of the production records of the 611 pairs of dams and daughters gives a similar result as 192 daughters were better than their dams in both quantity of milk and percentage of butterfat, and 104 were poorer in both, making a total of 296 cases where quantity of milk and percentage of butterfat moved together. In 315 cases one factor was raised and the other lowered, 134 daughters exceeded their dams in milk production but fell below in percentage of butterfat, while the other 181 daughters produced less milk but raised the average butterfat percentage.

SUMMARY AND CONCLUSIONS

The 611 daughters produced 164 pounds more milk and had a 0.10 per cent higher butterfat test than their dams. This is a measure of the rate of progress made in a generation, through accepted breeding practices.

Permanent breed improvement in milk production can not be accomplished through female selection except by continued extensive culling which is costly and wasteful.

One of the most striking conclusions presented by this study is the extremely heterozygous genetic make-up of these animals in so far as the factors for milk production are concerned. Evidence of this condition crops up continuously as the data are reviewed.

Sires whose dams have milk records of more than 12,000 pounds appear to be better sires of milk production than are the sires from untested dams or from dams with records of less than 12,000 pounds, when mated to cows with records of 9,000 to 13,000 pounds of milk.

Sons of cows having a butterfat test of more than 4 per cent sired daughters testing somewhat higher than did the daughters by sons of untested dams or the sons of dams testing below 4 per cent.

With small numbers of pairs of dams and daughters as here studied there is no indication that coefficients of correlation or variability have any significance in determining the breeding value of males or females.

It is doubtful if very many sires will ever have a sufficient number of daughters to offer suitable statistical material.

The cow's record indicates her milk-producing ability but is not an infallible guide as to her transmitting ability.

It appears that very little information regarding the inheritance of milk and butterfat production in dairy cattle will be evolved from studies of advanced-registry records: (1) Because of the heterozygous condition of the animals dealt with, (2) because they come from a very small and unfairly selected portion of the total dairy-cattle population, and (3) because of the lack of control of environmental conditions which so strongly influence milk and butterfat production of dairy cows.

The Mendelian laws of inheritance are adequate to explain all breeding results surveyed here when due allowance is made for the effects of a fluctuating environment. There is no evidence in these data for the assumption of sex linkage in the inheritance of milk production.

The influence of good sires is best illustrated by the average increase in milk production made by the daughters of a selected group of 10 sires. This increase was more than eight times as much as for the entire group of sires.

This study of the results which have come from the practices followed by the leading breeders of Ayrshire cattle during the period reviewed strengthens the theory that substantial improvement in dairy-cattle breeding can be made only by a better choice of herd sires. In all cases where groups of bulls were selected on a basis of their performance the results show the soundness of the use of proved sires for herd improvement.

Evaluating the transmitting ability of a proved sire requires a complete analysis of the performance of all his daughters, due consideration being given to the environmental influences. This necessitates a study of the herd in which the sire was proved. Correction factors designed to equalize these environmental influences are of questionable value, as there are no descriptive terms that will adequately define the variable conditions under which cows are tested. The certainty of success in breeding for uniformly high production is a sufficient incentive to cause the foresighted breeder to train himself to study and analyze performance records in order properly to select a proved sire. A generation ago much effort was applied to pedigree analysis, and the same amount of effort devoted to mastering the intricacies of record analysis and proper interpretation will equip a breeder properly to select sires for his herd.

The authors are of the opinion that no so-called bull index in existence to-day is so formulated as to afford a guide to constructive breeding procedure. At best, the bull index gives only a relative assay of the value of an animal as a sire. In a group of poor sires the one with the best index would still fail as a sire of daughters of high-milk production.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	HENRY A. WALLACE.
Assistant Secretary	REXFORD G. TUGWELL.
Director of Scientific Work	A. F. WOODS.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Chief.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Dairy Industry	O. E. REED, *Chief.*
Division of Dairy Cattle Breeding, Feeding, and Management	R. R. GRAVES, *Chief.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

Technical Bulletin No. 348 April, 1933

USE OF THE EXPONENTIAL YIELD CURVE IN FERTILIZER EXPERIMENTS

BY

W. J. SPILLMAN

Principal Agricultural Economist
Division of Farm Management and Costs
Bureau of Agricultural Economics

United States Department of Agriculture, Washington, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - - - - - - Price 10 cents

TECHNICAL BULLETIN No. 348 APRIL, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

USE OF THE EXPONENTIAL YIELD CURVE IN FERTILIZER EXPERIMENTS

By W. J. SPILLMAN

Principal Agricultural Economist, Division of Farm Management and Costs, Bureau of Agricultural Economics [1]

CONTENTS

	Page
Introduction	1
Yield curve for a single variable growth factor	5
Determination of the constants of the exponential curve	5
Graphic method	5
Logarithmic method	7
New method	9
Demonstration using experimental results with three variable factors	16
Ammonia series	19
Phosphoric acid series	20
Potash series	21
All three variables taken together	21
Final calculated yields	25
Yield of check plots	25
Optimum fertilizer formulas	27
Optimum quantity of fertilizer	32
Demonstration using experimental results with three variable factors—Continued	
Optimum acreage to which to apply fertilizer costing a fixed amount	36
Absorption, or occlusion, of plant food	41
Form of the yield curve	46
Derivation of the exponential yield curve	51
One-variable form	51
General form	54
Plan for obtaining data	55
Series of plots	56
Use of check plots	57
Other factors to be considered	58
Summary	59
Appendix	59
Tables of value of R^x and $1-R^x$	59
Literature cited	66

INTRODUCTION

The objective of early experimental work with fertilizers was to find which of the necessary plant-food elements the soil could, and which it could not, supply in quantities sufficient for the needs of the growing crop.

It was soon learned that the plant-food elements most commonly deficient in the soil are nitrogen, phosphorus, and potassium. Accordingly, these three elements were widely used in fertilizer tests, the aim being to determine the relative degree of deficiency of each in specific cases. These tests gave results of sufficient value to permit the development of an extensive fertilizer industry. Other experiments have had for their object a comparison of different sources of the various plant-food elements. Such experiments are necessary in any system of experimentation with fertilizers.

Recognition of the fact that nitrogen, phosphoric acid, and potash are most frequently needed in fertilizers made it obvious that experiments of two kinds were needed. One kind had for its object the determining of the most profitable combination of fertilizer elements, that is, the most profitable fertilizer formula, for a given soil and crop;

[1] Doctor Spillman died July 11, 1931. In the uncompleted manuscript acknowledgment was made of the valuable aid rendered by Mrs. Florence O. Thomas in making the computations, and by S. W. Mendum, Senior Agricultural Economist, in offering suggestions as to arrangement and presentation of the subject matter of the report. After Doctor Spillman's death Mr. Mendum completed the manuscript.

155743°—33——1

the other kind had for its object the determining of the most profitable quantity of this most profitable formula.

One group of experimenters gave particular attention to the problem of best fertilizer formulas, and devised an ingenious and effective system of experimentation which has given valuable information as to best formulas for given cases.

Others instituted series of experiments intended to determine the most profitable quantities of the various fertilizer elements and the various combinations to use in given cases.

The results of these two lines of experimentation are the basis of present fertilizer practice in the United States.

To cover the full range of fertilizer formulas and the full range of quantities of even a few formulas requires a large number of experimental plots. To obtain adequate answers to the problems of best formulas and best quantities of fertilizers to apply in a given case by the methods mentioned therefore entails large expenditures of both time and funds.

An equation expressing even approximately the relation between plant growth and quantity of plant food applied in fertilizers would enable the experimenter to carry on investigations of both these problems with a relatively small number of experimental plots. At the same time it would give more accurate answers to the two problems than could be otherwise obtained.

The economic bearing of such an equation is obvious. The ability to determine even approximately the formula for any quantity of fertilizer that will give the most profit, and the quantity of fertilizer made according to the best formula for that quantity that would result in the greatest profit per acre, should lead to less waste and greater profit in the use of fertilizer.

A large number of experiments have been performed in which the quantity of one or more growth factors was varied. When the results of these experiments are graphed, yields being used as ordinates and quantities of a growth factor as abscissas, a large proportion of the resulting curves are strikingly similar in form. (Fig. 1.) In fact, the proportion is so large as to suggest that in many cases those that do not give such a curve fail to do so because of large experimental errors in the work.

A curve that can be fitted satisfactorily to these experimental results would make it possible to calculate the yield from any quantity of the growth factor in question, the only experimental data needed being those required for finding accurate values for the constants of the equation.

In recent years it has been shown that either of the equations

$$Y = M - AR^x \tag{1}$$

or

$$y = a + bx + cx^2 \tag{A}$$

meets these requirements. Within the range of the data used in determining the constants in either of these equations, each gives a curve that fits experimental results satisfactorily. Over a considerable proportion of their range the two curves are closely similar in form.

It is shown later, however, that equation (1) has certain important advantages as compared with equation (A). It may be used with satisfactory results for calculating yields far beyond the limits of the experimental results used in determining the constants of the equation. This is not the case with equation (A).

An even more important advantage of equation (1) is that it may be written in a generalized form (p. 22) that permits it to be used, when its constants have been determined, for calculating the yield to be expected from any combination of fertilizer elements, in any quantity of fertilizer. Again, the generalized form of the equation by differentiation may be converted into a set of equations, one for each variable growth factor, by means of which the most profitable quantities of nitrogen and potash to use with any quantity of phos-

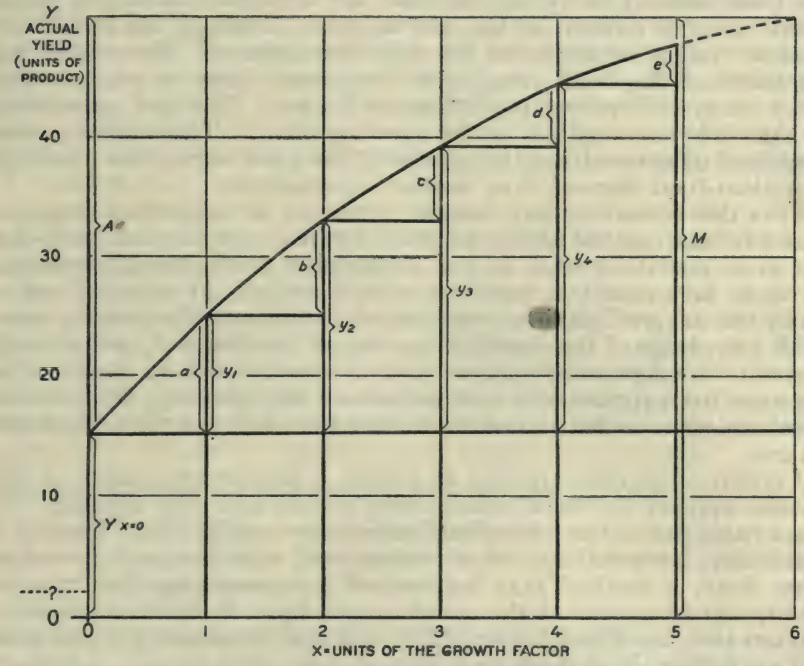


FIGURE 1.—EXPONENTIAL YIELD CURVE FOR A SINGLE VARIABLE GROWTH FACTOR

Y_0 is the yield when none of the factor is applied in fertilizer, y_1 the increase in yield due to 1 unit of the factor applied in fertilizer, y_2 the increase for 2 units, and so on. Y is the actual yield for x units of the factor, and M and A are the respective limits approached by Y and y as x increases indefinitely. Lines a, b, c, d, etc., are the increments in yield due to the first, second, third, fourth, etc., units applied. These increments tend to form a decreasing geometric series, of which R is the ratio.

phoric acid, as well as the most profitable quantity of this most profitable combination to use in a given case, can be determined.

These facts appear to justify at least the tentative adoption of equation (1) as the mathematical expression of the quantitative relation between plant growth and the quantity of a growth factor available. Further research may result in a more accurate expression for this relation. But the fact that equation (1) does permit satisfactory curve fitting, and thus greatly reduces the amount of experimental

work required for at least an approximate solution to both the problem of best formula and the problem of best quantity of fertilizer having this formula, would seem to justify the tentative use of the equation as a basis for planning and interpreting experimental work with fertilizers.

The uses to which equation (1) and its generalized form adapted to two or more variable growth factors may be applied are set forth in the following pages.

On certain soils very small applications of a fertilizer constituent give no increase in yield. As the quantity applied increases, a point is finally reached beyond which the yield begins to increase, and the increase proceeds from that point to follow a well-defined curve of normal increase. The small quantity thus having no effect on yield has been referred to by soil chemists as "absorbed" nitrogen, phosphoric acid, or potash, as the case may be. Perhaps the term "occlusion" might be preferred for this phenomenon. The reason for the failure of the small quantity of the growth factor to produce any effect on yield is as yet not definitely known. The fact appears to be that it is not available to the growing plant. This bulletin gives a method of determining, by means of the yield curve, the quantity of a plant-food element thus rendered unavailable.

This determination has economic value. It sometimes happens that a farmer can not obtain as much fertilizer as he knows he needs, but must distribute what he can obtain over a considerable acreage. It would be a complete waste to apply less than the quantity taken up by the soil and held in a condition unavailable to the growing crop. With knowledge of the quantity that would be absorbed, or occluded, and thus rendered unavailable, and of the increase in yield to be expected from applications over and above this quantity, the fertilizer obtainable can be distributed at the rate that will give the highest net return.

Certain other soils are said to absorb a definite proportion of the potash applied to them, irrespective of the quantity applied. In these cases the method described herein is not applicable. There is a possibility, however, that when further work with the yield curve has been done, a method may be devised for measuring this type of absorption by means of the curve, especially if it should be demonstrated that the effect factor (*11*) [2] of potash is constant for all soils not exhibiting these absorption phenomena.

The fact that the yield curve offers a means of determining from the yield of a relatively small number of experimental plots, the quantities of available nitrogen, phosphoric acid, and potash in the soil, makes the curve available for determining (1) the quantity of available nitrogen added to the soil by a green-manure crop; (2) the effect of lime or other soil amendments, including tillage practices, on the availability of plant-food elements in the soil; (3) the rate at which each plant-food element is exhausted in any system of crop management; and (4) the rate at which plant-food elements accumulate in the soil when fertilizers are applied in excessive quantities, thus permitting judicious modification of fertilizer practice with a view to preventing extravagant use of fertilizers which may result in accumulations that might become injurious to the crop.

[2] Italic numbers in parentheses refer to Literature Cited, p. 66.

YIELD CURVE FOR A SINGLE VARIABLE GROWTH FACTOR

The form of yield curve employed in this bulletin is known as the exponential yield curve. Its derivation and the reasons for preferring it are discussed later (p. 51). The curve assumes different shapes for different numbers of variable growth factors. The form assumed when a single growth factor is varied is shown in Figure 1. The equation of this form is

$$Y=M-AR^x, \qquad (1)$$

in which Y is the yield obtained when x units of the growth factor are applied in fertilizers, the unit being any convenient quantity of the factor. M is the limit approached by Y as x increases indefinitely, or the theoretical maximum yield possible with any number of units of the growth factor. A is the theoretical maximum increase in yield obtainable by increasing x indefinitely. R is the ratio of a decreasing geometric series the terms of which are the respective increments in yield due to successive unit increments in x. In Figure 1, lines a, b, c, d, e, etc., represent these increments; R is therefore the ratio of the series a, b, c, d, e, etc. This means that if b is a given percentage of a, then c tends to be the same percentage of b, d this same percentage of c, and so on.

The value of R in any given case depends on the size of unit in which x is measured, on the nature of the variable growth factor, and on the conditions of the experiment.

In Figure 1, $Y_{x=0}$ is the yield when none of the growth factor is supplied in fertilizers; that is, it is the yield due to the quantity of the growth factor available in the unfertilized soil. M is the limit approached by the curve as x increases indefinitely. The line at height M is an asymptote to the curve. The question mark at the lower left corner of the figure merely calls attention to whatever quantity of the growth factor may be available in the soil.

DETERMINATION OF THE CONSTANTS OF THE EXPONENTIAL CURVE

Several methods are available for finding the value of the constants of the yield equation. These vary in the reliability of the values found. Some of them are given below.

To illustrate these methods, and to compare the results they give, some results obtained by the Michigan Agricultural Experiment Station in applying varying quantities of potash (K_2O) to potatoes grown on muck soil are used. In addition to potash, each plot received phosphoric acid (P_2O_5) at the rate of 300 pounds of 16 per cent superphosphate per acre. One hundred pounds of 50 per cent muriate of potash (50 pounds of K_2O) is taken as the unit of x.

The yields per acre of four plots thus fertilized were:

Plot 1 (no potash)	91 bushels.
Plot 2 (1 unit of potash)	251 bushels.
Plot 3 (2 units of potash)	331 bushels.
Plot 4 (3 units of potash)	381 bushels.

GRAPHIC METHOD

A crude but simple and often useful method of finding at least a rough approximation to the value of the constants of the yield equation is as follows:

First, graph the experimental results, as is done in Figure 2 for the data given above. After fixing each point representing a yield, draw

through these points as smooth a curve as may be and as nearly as possible of the form shown in Figure 1. If the yields correspond closely to the theory of the curve, as they appear to do in Figure 2, the curve will pass through, or very near to, each point; but if the yields are irregular, the experimental errors being large, the curve should be drawn of the general form of Figure 1, more or less steeply according to the location of the dots, and as nearly as possible in such manner as to make the squares of the deviations a minimum. The deviations here referred to are the vertical distances of the yield points from the curve.

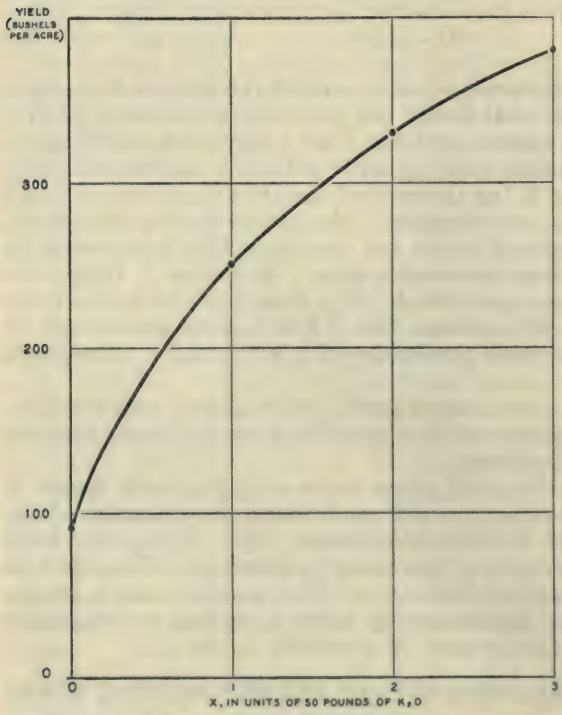


FIGURE 2.—PRELIMINARY DETERMINATION OF R

The actual yields are plotted, and a smooth curve of the form of Figure 1 is drawn as nearly as may be through the points.

Equation (1) may now be written for three points on the curve of Figure 1, these points being chosen in the following way:

One of the points should have the smallest and another the largest abscissa for which the yield is known, or can be read from the curve; the third point should have an abscissa half way between those of the other two.

For the curve of Figure 2, the points that meet these requirements are those whose abscissas are 0, 1.5, and 3. The corresponding values of Y are 91, 295 (read from the curve), and 381.

Using equation (1) for these three points, the observation equations are

$$91 = M - A \quad \text{(A)}$$
$$295 = M - AR^{1.5} \quad \text{(B)}$$
$$381 = M - AR^{3} \quad \text{(C)}$$

To evaluate R, subtract (A) from (B) and (B) from (C), giving

$$204 = A - AR^{1.5} = A(1 - R^{1.5}) \quad \text{(D)}$$
$$86 = AR^{1.5} - AR^{3} = AR^{1.5}(1 - R^{1.5}) \quad \text{(E)}$$

Dividing (E) by (D),

$$R^{1.5} = \frac{86}{204} = 0.42157.$$

Then

$$1.5 \text{ Log } R = \log 0.42157 = \bar{1}.624{,}8697 = -0.375{,}1303$$
$$\text{Log } R = -0.250{,}0869 = \bar{1}.749{,}9131$$

whence

$$R = 0.56223.$$

Since

$R^{1.5} = 0.42157$, it follows that $1 - R^{1.5} = 0.57843$.

From (D), it is seen that

$$A = \frac{204}{0.57843} = 352.68.$$

The value of M may now be obtained from any one of the equations (A) to (C). From (A)

$$M = 91 + A = 91 + 352.68 = 443.68$$

The values of R^x are then found to be:

For plot 1 (no potash)	1. 00000
For plot 2 (1 unit of potash)	. 56223
For plot 3 (2 units of potash)	. 31610
For plot 4 (3 units of potash)	. 17772

Using the indicated values of M, A, and R^x in equation (1) the calculated yields are: Plot 1, 91 bushels; plot 2, 245.39 bushels; plot 3, 332.2 bushels; and plot 4, 381 bushels. The calculated yields differ from the observed yields by 5.61 bushels on plot 2 and by 1.2 bushels on plot 3. Squaring each and adding, the sum of the squares of the differences between calculated and observed yields on the four plots (two of which are zero) is 32.9121. Values of M, A, and R, which give the smallest sum of squared differences or residuals are the most probable values. The roughness of the method and size of the sum (32.9121) suggest that better values for the constants may be found.

LOGARITHMIC METHOD

The logarithmic method may be used for determining the values of M, A, and R of the exponential yield curve in cases where the successive observations result in positive increments as x increases. If any observation is a smaller number than the previous observation this method can not be used, as a negative number as such has no logarithm.

Letting z represent the increment of Y due to a unit increment of x, equation (1), $Y = M - AR^x$, becomes

$$Y + z = M - AR^{x+1} \qquad \text{(A)}$$

whence by subtraction

$$z = AR^x - AR^{x+1} = AR^x(1-R) = A(1-R)R^x$$

and

$$\text{Log } z = \log [A(1-R)] + x \log R \qquad \text{(B)}$$

Equation (B) is solved by the method of least squares, for which the form used in Table 1 is convenient. The observations are entered in the columns at the left. The values of z are then entered opposite the corresponding values of x and the observation equations

(C), (D), and (E) are made up by substituting the proper values for log z and for x.

TABLE 1.—*Example of work for determining R and A by the logarithmic method*

$$[\text{Log } z = \log [A(1-R)] + x \log R] \qquad \text{(B)}$$

Plot No.	x	Y	z	Log z	Coefficient of log $[A(1-R)]$	Coefficient (x), of log R	Reference
1	0	91	160	2.2041200	1	0	(C)
2	1	251	80	1.9030900	1	1	(D)
3	2	331	50	1.6989700	1	2	(E)
4	3	381					

Sum of (C), (D), and (E) $5.8061800 = 3 + 3$ (F)
Sum of (D) and 2 times (E) $5.3010300 = 3 + 5$ (G)

Subtract (F) from (G) $-0.5051500 = +2$

$$\text{Log } R = -.2525750 = \bar{1}.7474250;$$
$$R = 0.559017$$
$$1-R = 0.440983$$

$$3 \log [A(1-R)] = 5.8061800 - 3 \log R \qquad \text{(F)}$$
$$= 5.8061800 + 0.7474250$$
$$= 6.5639050$$
$$\log [A(1-R)] = 2.1879683$$

But $$\log (1-R) = \bar{1}.6444218$$

Hence $$\log A = 2.5435465$$

and $$A = 349.58$$

The normal equation (F) for log $[A(1-R)]$ is obtained by adding the three observations as they stand, since the coefficient of this unknown is 1 in each observation equation.

The normal equation (G) for log R is obtained by multiplying each observation equation through by the coefficient of log R in that equation and adding the resulting equations.

Equations (F) and (G) are then solved by the usual methods of algebra, and the values of A and of R are obtained therefrom, as indicated in Table 1.

The value of M is found by writing an observation equation based on equation (1) for each value of x, thus

$$91 = M - A$$
$$251 = M - AR$$
$$331 = M - AR^2$$
$$381 = M - AR^3$$

Since the coefficient of M is 1 in each of these equations, the normal equation for M is the sum of the four as they stand, or

$$1{,}054 = 4M - A(1 + R + R^2 + R^3)$$

whence

$$M = \frac{1}{4}[1{,}054 + A(1 + R + R^2 + R^3)]$$

But the values of A (349.58) and of R (0.559017) have been found. (Table 1.)

The value of the parenthesis is

$$1.000000+0.559017+0.312500+0.174693=2.046210$$

Therefore

$$M=\frac{1}{4}\,[1{,}054+349.58(2.046210)]=442.33$$

Using these values of M, A, and R the computed yields of the four plots are 92.75 bushels on plot 1, 246.91 bushels on plot 2, 333.09 bushels on plot 3, and 381.26 bushels on plot 4. The corresponding residuals from the observed yields were respectively 1.75, −4.09, 2.09, and 0.26. The sum of the squares of these residuals is 24.2263 as compared with the 32.9121 obtained by the graphic method. The logarithmic method thus gives better results than does the graphic method.

The value of an unknown determined by the method of least squares, called its most probable value, is the arithmetical mean of its value in each of the observation equations. Now the arithmetical mean of n quantities is $\frac{1}{n}$ of their sum.

The value of an unknown determined from the most probable value of its logarithm is therefore the geometric, not the arithmetical, mean of the measurements, direct or indirect, made on the unknown; for when the logarithms of n quantities are added, the sum is the logarithm of their product; when the sum is divided by n the quotient is the logarithm of the nth root of their product, which nth root is the geometric mean of the n quantities. The only condition under which the arithmetical and geometric means of a series of numbers are equal is that all numbers in the series be equal. This condition arises in statistical work only when there are no errors of observation, a condition that practically never occurs. Hence the value of a quantity obtained from the most probable value of its logarithm is not the most probable value of the quantity.

There is thus an error in the logarithmic method here outlined. The greater the errors of observation in the data employed, the greater is the magnitude of this error. With fairly good observed values the error is not large. To illustrate:

Arithmetical mean:

$$\frac{1}{4}\,(49+52+45+54)=50$$

Geometric mean:

$$\sqrt[4]{49.\ 52.\ 45.\ 54}=49.88$$

When the errors of observation are such as to render some of the values of z negative, the logarithmic method is not applicable at all, for a negative quantity, as such, has no logarithm.

NEW METHOD

The author's new method applies the principle of least squares directly to observation equations based on the equation (1), $Y=M-AR^z$. Development of the necessary normal equations in general terms is explained. Solution of the normal equations—finding the

most probable values of M, A, and R—has been reduced to plain arithmetic. Finding the value of R, however, can only be done by successive approximations, so that the work involved is formidable and should not be undertaken without adequate equipment for making the computations.

Using a, b, c, d ---- to represent observed values of x, and Y_a, Y_b, Y_c, Y_d ---- to represent corresponding values of Y, the several observation equations may be written:

$$\left.\begin{aligned} Y_a &= M - AR^a \\ Y_b &= M - AR^b \\ Y_c &= M - AR^c \\ Y_d &= M - AR^d \end{aligned}\right\} \quad (A)$$

and so on.

Normal equations for M, A, and R are worked out applying the general rule, of which the example used under the logarithmic method is a special case. This general rule for finding the normal equation for any variable in a set of observation equations is: Multiply each equation through by the derivative of that equation with respect to the variable in question and add the resulting equations. The derivatives of equation (1) with respect to M, A, and R are:

For M the derivative is 1.
For A the derivative is R^x.
For R the derivative is AxR^{x-1}.

The normal equation for M is therefore the sum of the observation equations (A) as they stand; this gives

$$\Sigma Y = nM - A\Sigma R^x,$$

from which, transposing and dividing through by n

$$M = \frac{1}{n}[\Sigma Y + A\Sigma R^x] \quad (2)$$

In these expressions ΣY is the sum of the quantities represented by Y_a, Y_b, Y_c, Y_d ----, n is the number of observation equations, and $A\Sigma R^x$ is the sum of the several values R^a, R^b, R^c, R^d ---- multiplied by A.

The normal equation for A is obtained by multiplying the first observation equation through by R^a (the value of R^x, the derivative of A in (A) above,) the second by R^b, and so on, and adding the resulting equations. The resulting normal equation may be reduced to the form

$$A = \frac{n\Sigma YR^x - \Sigma Y\Sigma R^x}{(\Sigma R^x)^2 - n\Sigma R^{2x}} \quad (3)$$

The normal equation for R, is obtained by multiplying the first observation equation through by AaR^{a-1}, (the derivative for R in (A) above), the second by AbR^{b-1}, and so on, and adding the resulting equations. The normal equation so written may be reduced for convenience of subsequent quantitative computation to the form

$$A' = \frac{n\Sigma YxR^x - \Sigma Y\Sigma xR^x}{\Sigma R^x\Sigma xR^x - n\Sigma xR^{2x}} \quad (4)$$

The A' of equation (4) and the A of equation (3) are identical in value; the prime mark is used in equation (4) as a convenient means of distinguishing between the two formulas.

SOLUTION OF THE NORMAL EQUATIONS

The problem of finding the most probable values of M, A, and R in equation (1) now resolves itself into that of finding that value of R that will make A' equal to A. This can be done only by the method of trial and error. The solution is demonstrated with the data considered under the graphic and logarithmic methods.

The procedure found to be most convenient for solving the equations is here given, using Table 2 in the demonstration. The quantities for which values are wanted as steps in the computation are entered on the blank form, and the values are entered as they are arrived at. Six sections were used in this problem and will usually be enough for finding the value of R. The actual working sheets should provide for as many lines as there are observation equations; for economy of printing only the four needed in this 4-plot problem are shown in Table 2. The symbols not previously used will be explained later; they are all used in other phases of the general problem and are provided for in the table.

The table of values of R^x, prepared by Y. Kutsunai of the Hawaiian Sugar Experiment Station (Table 18), reduces the labor of computation materially.

LOCATING THE VALUE OF R

The most probable values of M, A, and R are those that render the sum of the squares of the residuals a minimum. The residuals are the remainders obtained by subtracting the observed values from the calculated values of Y. For the problem now in hand the sum obtained by the graphic method was 32.9121; that obtained by the logarithmic method was 24.2263. Hence the values of M, A, and R obtained by the logarithmic method approach more nearly the values sought than those obtained by the graphic method.

The values of R found by these two methods were—

By the graphic method, $R=0.56223$.

By the logarithmic method, $R=0.559017$.

Since the second value of R is smaller than the first and the sum of the squared residuals is smaller than for the other, it is probable that the most probable value of R is smaller than 0.559017. Computation by the author's method may then start with $R=0.55$. (The alternative to use of either of the above methods or both for approximating the value of R as a preliminary to computation by the author's new method is more trials by the more onerous method.)

In the upper left section of Table 2 trial is made with $R=0.55$. Opposite the given values of x are placed the observed values of Y, then the corresponding values of R^x, the values of R^3 and higher powers of R being obtained from Table 18. The figures in the column headed xR^x are the indicated products of the figures in the first and third columns. The figures in the column headed R^{2x} are the squares of those in the column headed R^x. By addition the values of ΣY, ΣR^x, ΣxR^x, and ΣR^{2x} are obtained.

The next step is to find the value of A and of A', equations (3) and (4). The numerator of equation (3), N, consisting of a positive term, $n\Sigma YR^x$, and a negative term, $-\Sigma Y\Sigma R^x$, is worked. Then the denominator, D, is worked out, the division performed, and the value of A ($=346.161475$) set down. The value of A' is found in the same way.

TABLE 2.—*Arrangement*[1] *of work for computing R, M, and A by the new method. Same data as in graphic and logarithmic methods*

$Y=M-AR^x$ $\quad A=\frac{N}{D}$ $\quad N=n\Sigma YR^x-\Sigma Y\Sigma R^x$ $\quad D=\Sigma R^x\Sigma R^x-n\Sigma R^{2x}$

$M=\frac{1}{n}(\Sigma Y-A\Sigma R^x)$ $\quad A'=\frac{N'}{D'}$ $\quad N'=n\Sigma YxR^x-\Sigma Y\Sigma xR^x$ $\quad D'=\Sigma R^x\Sigma xR^x-n\Sigma xR^{2x}$

n=number of observations=4 $\quad E=A-A'$ $\quad q=(\log M-\log A)/\log R$

Item	x	Y	R^x	xR^x	R^{2x}	R^x	xR^x	R^{2x}
1	0	91	1.0	0.0	1.0	1.0	0.0	1.0
2	1	251	.55	.55	.3025	.54	.54	.2916
3	2	331	.3025	.6050	.091506	.2916	.5832	.085031
4	3	381	.166375	.499125	.027681	.157464	.472392	.024795
Σ	----	1,054	2.018875	1.654125	1.421687	1.989064	1.595592	1.401426

N	1,570.2655 −2,127.894250= −557.628750	1,532.213536−2,096.473456= −564.259920
D	4.075856− 5.686748= − 1.610892	3.956376− 5.605704= − 1.649328
N'	2,113.8865 −1,743.447750= 370.438750	2,034.242208−1,681.753968= 352.488240
D'	3.339472− 2.274220= 1.065252	3.173735− 2.144188= 1.029547
A	346.161475	342.115043
A'	347.747528	342.372170
E	−1.586053	−.257127

Item	x	Y	R^x	xR^x	R^{2x}	R^x	xR^x	R^{2x}
1	0	91	1.0	0.0	1.0	1.0	0.0	1.0
2	1	251	.538	.538	.289444	.539	.539	.290521
3	2	331	.289444	.578888	.083778	.290521	.581042	.084402
4	3	381	.155721	.467163	.024249	.156591	.469773	.024521
Σ	----	1,054	1.983165	1.584051	1.397471	1.986112	1.589815	1.399444

N	1,524.694660−2,090.255910= −565.561250	1,528.450488−2,096.473456= −564.259920
D	3.932943− 5.589884= − 1.656941	3.944641− 5.597776= − 1.653135
N'	2,018.556124−1,669.589754= 384.966370	2,026.389660−1,675.665010= 350.724650
D'	3.141345− 2.118088= 1.022447	3.157551− 2.131552= 1.025999
A	341.328539	341.721372
A'	341.305095	341.837224
E	.023444	−.115852

Item	x	Y	R^x	xR^x	R^{2x}	R^x	xR^x	R^{2x}
1	0	91	1.0	0.0	1.0	1.0	0.0	1.0
2	1	251	.5381	.5381	.289552	.5382	.5382	.289659
3	2	331	.289552	.579104	.083840	.289659	.579318	.083902
4	3	381	.155808	.467424	.024276	.155895	.467685	.024303
Σ	----	1,054	1.983460	1.584628	1.397668	1.983754	1.585203	1.397864

N	1,525.070640−2,090.566840= −565.496200	1,525.445296−2,090.876716= −565.431420
D	3.934114− 5.590672= − 1.656558	3.935280− 5.591456= − 1.656176
N'	2,019.340272−1,670.197912= 349.142360	2,020.121772−1,670.803962= 349.317810
D'	3.143046− 2.120240= 1.022806	3.144653− 2.121488= 1.023165
A	341.368186	341.407809
A'	341.357364	341.409069
E	.010822	−.001260

x	R^x	AR^x	M	Y (calculated)	Y (observed)	e	e^2
0	1.0	341.40	432.81	91.41	91	0.41	0.1681
1	.538188	183.74	432.81	249.07	251	−1.93	3.7249
2	.289646	98.89	432.81	333.92	331	2.92	8.5264
3	.155884	53.22	432.81	379.59	381	−1.41	1.9881
------	1.983718	----------	----------	----------	----------	----------	14.4075

	Logarithms
R 0.538188	−0.2690660
A 341.401	2.5332635
M 432.81	2.6362973

Unit of x 50 pounds of K_2O.
q=0.3829 units=19.145 pounds per acre.

[1] The author's work sheets were mimeographed blank forms, with spaces provided for 8 values of x. The blank lines have been omitted in printing. See text for development of the work recorded on this form. Table 18 and a computing machine are practical necessities.

To obtain the value of the positive term, $n\Sigma YR^z$, of N, for example, set up 91 (=91 times 1.0) in the computing machine; add to it 251 times 0.55; add to that 331 times 0.3025; and then 381 times 0.166375; the sum so accumulated (the ΣYR^z) is then multiplied by n, in this case 4. The result, 1,570.265500 is recorded as the first term of N in the line below the columns of Table 2.

The second (negative) term of N is $\Sigma Y\Sigma R^z = 1{,}054$ times $2.018875 = 2{,}127.894250$. The algebraic sum of the two terms of N is -557.628750.

The reader should now be able to follow the procedure in obtaining the values of D, N', and D'.

Note that the negative terms of both N and D are larger than the positive terms. If the positive terms are computed first they may be subtracted from the negative terms without resetting the negative terms in the machine. The negative terms of N' and D' are smaller than the positive and may be advantageously computed first.

The difference E, between A and A' in this case, with $R = 0.55$ is -1.586053. When the correct value of R is obtained, E will be zero. Under the conditions of this problem a negative value of E indicates that the value of R under test is too large. (See discussion of critical values of R below for conditions indicating the opposite situation.) Accordingly the value of $R = 0.54$ is tried. (The computations are shown in the upper right section of Table 2.) This time E becomes -0.257127, much nearer zero, but still negative, indicating that R is somewhat less than 0.54.

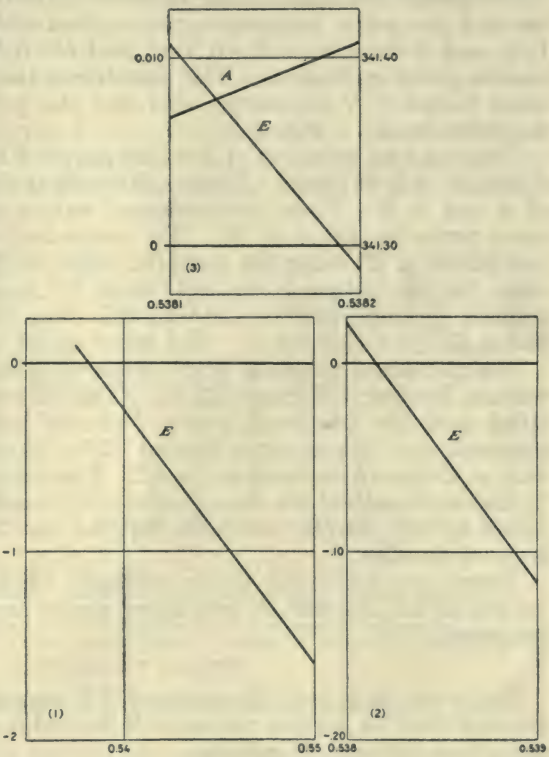


FIGURE 3.—STEPS IN THE DETERMINATION OF A AND R

In section 1, the values of E found in Table 2 are plotted. The line crosses the zero line at about 0.538. The value for E at 0.538 is positive (sec. 2), hence too small; so the value at 0.539 was computed, the line drawn through these points indicating a value between 0.5381 and 0.5382. Plotting the values of E and of A at these values and drawing the lines (sec. 3) gives the true values sought, R=0.538188 (E is 0 at this point), and A=341.401 for this value of R.

With two values of E available, some work may be saved by graphing the values as in Figure 3 (1) before proceeding with further trials. A line drawn through the two computed values of E crosses the zero line at about 0.538. Hence the next value of R tested is 0.538. It should be noted here that the graph of E is somewhat curved, being convex downward. This curvature of the graph of E is the more marked the fewer the decimal places in the value of R under test.

Because of this curvature, the straight line used does not give the exact value of R, as the true graph of E probably crosses the zero line somewhat to the right of 0.538.

The value of E when R is placed at 0.538 comes out 0.023444, positive, indicating that R is greater than 0.538. The value of E when R is placed at 0.539 is -0.115852, negative, indicating a value of R less than 0.539. These last two values of E are graphed on a larger scale in Figure 3 (2), the E line crossing the zero line at about 0.53818.

Ordinarily it would not be necessary to carry the computation of R beyond this point, but since a comparison is desired between methods 1, 2, and 3 the values $R=0.5381$ and $R=0.5382$ are tested with the results given in Table 2. The line drawn through the values of E for these values of R crosses the zero line at a point indicating a value of 0.538188 for R. (Fig. 3 (2).)

The last two values of A are also graphed in Figure 3 (3). At $R=0.538188$ A is 341.401. These are taken as the most probable values of A and of R. These two accepted values are then used to find the most probable value of M. The steps in finding M are: Compute the values of R^x using the accepted value of R, entering them on the form (at the bottom); multiply each by A and enter them; add this column (giving $A\Sigma R^x$). Add to this sum the sum of the observed yields (ΣY); divide by n. The value of M comes out 432.81.

The calculated values of Y are obtained subtracting each value in the column headed AR^x from 432.81. The differences between the calculated and the observed yields (column headed "e") are entered, squared, and the squares totaled ($\Sigma e^2=14.4075$). The smaller this sum is, the more accurate is the fit. The values of M, A, and R found by the new method are thus considerably more satisfactory than those found by the simpler methods, for the sum of the squared residuals is much smaller.

There are numerous other methods of finding the approximate values of M, A, and R, but those given are sufficient for practical purposes.

CRITICAL VALUES OF R

The work of finding the value of R is complicated in some cases by the fact that for certain values of R the value of D' (Table 2) becomes zero, thus making A' infinite.

When the values of x used include zero, and consist of the consecutive numbers 0, 1, 2, 3, etc., D' is always positive, so that the complication mentioned does not occur. In these cases E is positive for all values of R less than the true value, and negative for all values greater than the true value.

But if the given values of x do not include zero, and consist of the consecutive numbers 1, 2, 3, 4, etc., then there is always a value of R, here called its critical value, for which $D'=0$. The critical values of R for series of x values commonly occurring in experimental work are as follows:

Series of x values	Critical value of R
1, 2, 3, 4	0. 621173
1, 2, 3, 4, 5	. 661689
1, 2, 3, 4, 5, 6	. 694225
1, 2, 3, 4, 5, 6, 7	. 720886
1, 2, 3, 4, 5, 6, 7, 8	. 743354
1, 2, 3, 4, 5, 6, 7, 8, 9	. 762477

Let R_m represent the most probable value of R,
R_t the value under test, and
R_c the critical value.

Figure 4 and the relations stated in tabular form below will aid in determining whether a given positive or negative value of E indicates that R_t is too large or too small.

In each of the three drawings of Figure 4 the abscissas are values of R, while the ordinates are values of A and A'. The most probable value of R, symbolized by R_m, is the abscissa of the point, X, at which the graph of A' crosses that of A. At this point $A'=A$ and $E=0$. The critical value of R, symbolized by R_c, is the abscissa of the point at which D' (not shown in the drawing) becomes zero and A' becomes infinite.

It is readily seen in Figure 4 (1), which represents cases having no critical value for R, that is, in which D' does not become zero for any value of R, that a positive E shows R_t to be too small, while a negative E shows R_t to be too large.

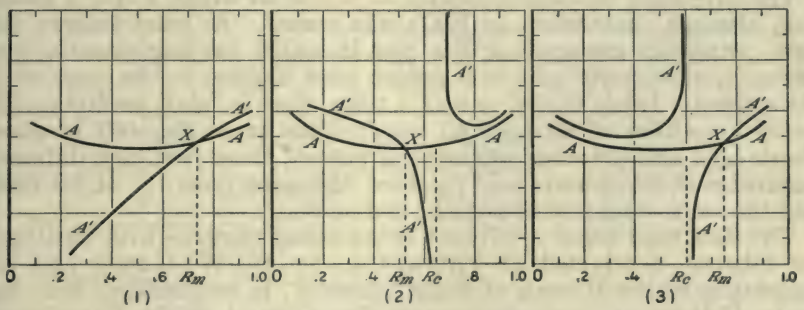


FIGURE 4.—GRAPHS OF THE VALUES OF A AND A'

A and A' are equal at some value of R, called its most probable value (R_m). In experimental series which do not include a value for $x=0$ there is always a critical value of R (R_c) which renders A' infinite. Section 2 illustrates cases in which R_m is smaller than R_c; section 3, cases when R_m is larger than R_c. Section 1 covers those cases in which the values of x are consecutive numbers beginning with 0.

In Figure 4 (2) and Figure 4 (3) the relations between R_t and R_m may be stated as follows:

When preliminary tests (by the graphic or the logarithmic method indicate that R_m is less than R_c (fig. 4 (2)), then a negative E indicates that R_t is too small and a positive E indicates that R_t is too large.

When R_m is greater than R_c (fig. 4 (3)), then a negative E indicates that R_t is too large and a positive E indicates that R_t is too small.

Occasionally R_m lies so near to R_c that the value of R_m determined by preliminary tests may lie on the wrong side of R_c. Suppose, for instance, that the preliminary value of R_m is slightly greater than R_c, (fig. 4 (3)), while the true value of R_m is slightly less than R_c (fig. 4 (2)). In such a case a few trials of R values greater than R_c will show that as R_t decreases, A' rapidly increases, which shows that Figure 4 (2) and not Figure 4 (3) applies.

If for values of R_t slightly less than R_c the value of A' increases rapidly for slight increases in R_t, then R_m is greater than R_c.

For irregular series of x values it is necessary to work out the values of D' for a series of R values to determine the critical value of R, if any such value exists.

AVAILABLE PLANT FOOD IN THE SOIL

The quantity of a plant-food element available in the soil without any fertilizer application, designated as q, may be computed at this stage. The value of q is the value of x in equation (1) when Y is zero; that is, q equals x in the equation $0=M-AR^x$, which reduces to

$$x=\frac{\log M-\log A}{\log R}=q \qquad (5)$$

This value of x is the point at which the yield curve crosses the x axis. This point lies to the left of the origin; hence q comes out negative. The negative sign is to be disregarded, for the origin was arbitrarily placed.

The data of this example show that q is 19.145 pounds of potash (K_2O) per acre. (Table 2.)

DEMONSTRATION USING EXPERIMENTAL RESULTS WITH THREE VARIABLE FACTORS

The preceding discussion relates to a case in which a single plant-food element (potassium as K_2O) was varied. In what follows the same principles are applied to a case in which varying quantities of nitrogen, phosphoric acid, and potash were applied to the same crop, the elements being varied one at a time; that is, plots receiving different quantities of nitrogen all received the same quantity of phosphoric acid and the same quantity of potash, those receiving different quantities of phosphoric acid received the same quantity of nitrogen and the same quantity of potash, and so on.

The data used below are from a series of experiments with fertilizers for tobacco, conducted at Tifton, Ga., by W. W. Garner and his associates, of the Bureau of Plant Industry, in cooperation with the State College of Agriculture and the Coastal Plain Experiment Station of that State. These data were kindly supplied by Doctor Garner.

The essential facts are given in Table 3.

TABLE 3.—*Fertilizers applied and yields obtained in the tobacco experiments at Tifton, Ga.*

[Rate of fertilizer application, 1,000 pounds per acre]

Plot No.	Analysis of fertilizer applied			Yields of tobacco per acre in—					
	NH_3	P_2O_5	K_2O	1924	1925	1926	1927	1928	1929
	Per cent	*Per cent*	*Per cent*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
1	5	8	5	1,235	1,571	1,219	1,329	1,182	1,452
2	4	8	5	1,281	1,572	1,224	1,201	1,051	1,262
3	3	8	5	1,206	1,499	1,157	1,252	975	1,073
4	2	8	5	1,094	1,398	1,092	1,351	930	972
5	0	8	5	867	1,129	914	1,427	693	966
6[1]	0	0	0	519	769	484	593	401	501
7	3	12	5	1,115	1,653	1,236	1,306	973	1,133
8	3	10	5	1,214	1,670	1,150	1,165	1,065	1,134
9	3	9	5	1,237	1,550	1,047	1,236	979	1,163
10	3	7	5	1,214	1,797	1,173	1,256	1,067	1,086
11	3	6	5	1,223	1,629	1,091	1,226	928	1,276
12	3	4	5	1,285	1,669	1,098	1,206	895	1,100
13	3	0	5	1,219	1,407	935	559	509	445
14[1]	0	0	0	785	770	729	530	495	518
15	3	8	8	1,293	1,733	1,239	1,441	1,132	1,039
16	3	8	6	1,156	1,735	1,187	1,318	1,040	1,138
17	3	8	4	1,199	1,752	1,064	1,211	1,026	930
18	3	8	3	1,115	1,518	1,102	1,249	943	1,190
19	3	8	2	1,184	1,347	1,074	1,166	856	909
20	3	8	0	590	1,018	697	981	576	834

[1] Check plot.

The yields shown in Table 3 are graphed in Figure 5. The graphs in the first column are based on the yields from plots 1 to 5, in which ammonia is the variable; those in the second column relate to plots 7 to 13, in which phosphoric acid is the variable; and those in the last column relate to plots 15 to 20, in which the variable is potash. The numbers attached to the lines indicate the year, the first year being 1924. The yields on all plots were extraordinarily high in the second year (1925). Where these yields were used they were reduced by a

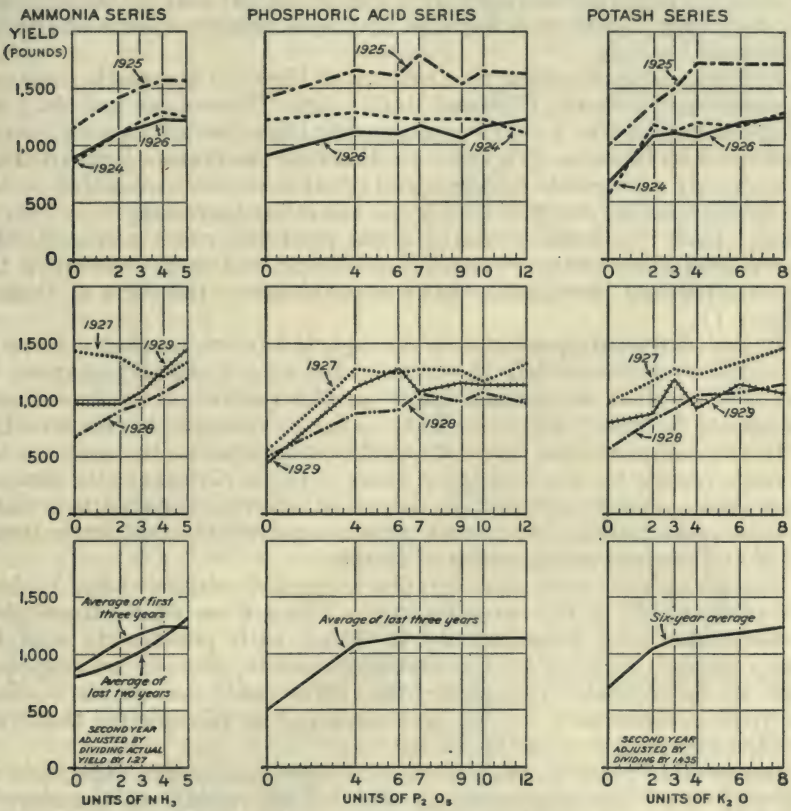


FIGURE 5.—YIELDS ON TOBACCO EXPERIMENTAL PLOTS AT TIFTON, GA., 1924–1929

These are the yields shown in Table 3 and the averages used in the computations. The separation into groups of three years is to avoid confusion of lines. The reasons for selecting the several averages are given in the text. The rate of application of fertilizer was 1,000 pounds per acre, and the unit of x (the growth factor) was 1 per cent, or 10 pounds, of each of the three plant foods.

factor which reduced the average of all nitrogen plots in 1925 to the average of the first and third years. This was done to avoid exaggeration of yields due to a very unusual season in 1925. The graphs in each column are separated into groups of three each to avoid confusion from so many overlapping lines and to bring out certain relations that are discussed below.

The graphs show a number of things of great interest. In the nitrogen series, curves 1 and 2 are almost identical in form, whereas curve 3 departs from this form very slightly. The graphs for later

years show, strikingly, a cumulative effect of the nitrogen. This effect begins to show plainly the fourth year, and is very marked in each year following, more so the sixth than the fifth year.

The hypothesis is suggested that after the experiment had continued for about three years the resulting cumulative effect of the increased organic matter, presumably from the decaying roots and stubble of the larger crops on the more heavily fertilized plots, began to affect the yield on the latter plots. The yields in these later years on the plots receiving much nitrogen were influenced not only by the nitrogen applied from year to year but also by the increasing reserve of organic matter in the soil.

In the lower part of the first column of Figure 5 a curve is shown of the average yields the fifth and sixth years. This curve has the form of the lower part of a curve representing the effect of varying two or more growth factors. (Fig. 11.) In this case the factors concerned are presumably nitrogen in fertilizer and plant food made available by the decay of remains from previous crops, the latter increasing from year to year. Had the series included plots receiving more nitrogen, this curve (including the part extending beyond the limits shown in the drawing) would presumably have approximately the form of that of Figure 11.

If the above interpretation is correct, it is obvious that a formula intended to express solely the relation between yield and quantity of fertilizer applied would not apply to the results of an experiment continued for many years, at least so far as nitrogen is concerned.

In the computations that follow, the ammonia results used are the average results for the first three years of the experiment (the second-year results being adjusted as described above), because the yields in later years presumably do not represent merely the relation between yield and current applications of fertilizer.

The phosphoric acid plots (graphs in second column of fig. 5) show the reverse side of the same picture. The soil on which these plots were located had been heavily fertilized with phosphoric acid for many years. Judging by the first-year results, the soil was supplied with all the available phosphates the plants could use, so far as effect on yield is concerned, for the plot receiving no phosphates that year yielded about as well as the others.

But as time went on, the situation changed markedly. The yield on the plot receiving no phosphoric acid fell off rapidly as the store of available phosphoric acid in the soil was reduced. The yields on this plot were very low and almost identical in each of the last three years. Apparently the rate of exhaustion of phosphoric acid on the no-phosphate plot (No. 13) was very rapid during the first four years, and by that time the phosphoric acid supply had nearly reached the minimum that the soil could develop regularly.

Doctor Garner stated that the effect of phosphates on the quality of tobacco is so marked that it pays to use more of this fertilizer constituent than is necessary from the standpoint of yield alone. This effect appears to be produced by influencing the date of maturity of the crop. To secure the best quality of product the crop must be harvested while the weather is still quite warm. Heavy applications of phosphates hasten maturity, and hence result in a product of higher quality.

In general, the longer the growing season of a crop the greater the yield, other things being equal, though exceptions to this rule occur. There is some evidence in the graph at the bottom of the middle section of Figure 5 that yields are slightly lower on those plots receiving the heaviest applications of phosphoric acid. This may be due to the increasing earliness of the crop with increasing doses of phosphates.

So far as yields alone are concerned, the results from the phosphate plots for the first year of the experiment are the only ones that give a true picture of the fertilizer relations of the soil at the time the experiment began. The yields that year indicate that the crop had all the phosphoric acid it could use in making increased yields. The curve for the average of the last three years (bottom of middle section of fig. 5) indicates, however, that it took about 60 pounds of phosphoric acid (P_2O_5) a year to maintain maximum yields. Quality of product may demand more than 60 pounds, possibly at the expense of slightly reduced yields due to earlier maturity of the crop.

In the computations that follow, use is made of average yields on plots 11, 12, and 13 of the phosphoric acid series for the last three years, for the reason that these yields permit an estimate of the reduction in yield due to earlier maturity caused by large phosphate applications, as will be seen later.

The potash curves in Figure 5 show neither the cumulative effect of heavy applications seen in the ammonia curves nor the exhaustive effect of light applications seen in the phosphoric acid curves. For this reason the average results for the six years were used in the computations, with the second-year results adjusted as previously stated.

The computed values found in what follows are not to be regarded as final, since these experiments were planned for a different purpose. Particularly the absence of a complete series of check plots affects the results from the standpoint of the present purpose. Nevertheless the results illustrate very satisfactorily the methods of computation required for a series of plots fertilized as suggested later in this paper.

It will be observed that the nitrogen data in Table 3 are given in units of ammonia. These data could easily be converted into terms of nitrogen, since a pound of ammonia contains fourteen-seventeenths of a pound of nitrogen. But this would necessitate carrying out extensive calculations with fractional values of x. The computations are therefore carried out on the ammonia basis. In the final results the conversion of pounds of ammonia into pounds of nitrogen may easily be accomplished.

AMMONIA SERIES

(Plots 1 to 5)

The yields used for the ammonia series were the average yields of plots 1 to 5 for the first three years of the experiment, with second-year yields reduced as previously explained. A preliminary reading on the value of R was obtained by the graphic method, and the values of M, A, and R in the equation $Y=M-AR^x$ were then calculated by the author's new method.

The results were

$$R=0.69787$$
$$A=436.02$$
$$M=1323.44$$

The unit of x used was 10 pounds of ammonia (NH_3) per acre. To check the values found, calculated and observed yields were compared as follows:

Plot	x	R^x	AR^x	Y (calculated)	Y (observed)	e
5	0	1.0	436.02	887.42	890	−2.58
4	2	.48702	212.35	1,111.09	1,095	16.09
3	3	.33988	148.19	1,175.25	1,181	−5.75
2	4	.23719	103.42	1,220.02	1,248	−27.98
1	5	.16553	72.17	1,251.27	1,231	20.27

The greatest residual is slightly more than 2 per cent of the corresponding observed yield, which must be considered fair agreement between theory and practice.

PHOSPHORIC ACID SERIES

(Plots 7 to 13)

The effect of phosphates in increasing yields is shown by those plots receiving 0, 40, and 60 pounds of phosphoric acid (P_2O_5). Higher applications gave no further increase; indeed, there appears to be a slight decrease in yield from them. This is presumably due to the effect of heavy applications in hastening the maturity of the crop. By using the yields from 0, 40, and 60 pounds of P_2O_5 some measure of this hastening effect can be obtained. The constants of the yield equation are, therefore, calculated from the yields of those plots receiving 0, 40, and 60 pounds of P_2O_5.

The observation equations based on these plots are:

$$\text{Plot 13, } x=0, \quad 504=M-A \tag{A}$$
$$\text{Plot 12, } x=4, \quad 1{,}067=M-AR^4 \tag{B}$$
$$\text{Plot 11, } x=6, \quad 1{,}143=M-AR^6 \tag{C}$$

There being three equations between the three unknowns, they may be solved directly by the methods of algebra.

Subtracting (A) from (B) and (B) from (C),

$$563=A(1-R^4) \tag{D}$$
$$76=AR^4(1-R^2) \tag{E}$$

Dividing (E) by (D),

$$\frac{R^4}{1+R^2}=0.13499112$$

The solution of this equation gives $R=0.66412$, whence $R^4=0.19453$.

Substituting this value of R^4 in (D), and dividing through by $(1-R^4)$,

$$A=\frac{563}{0.80547}=698.97,$$

whence, using equation (A) since $Y_0=504.00$, $M=1202.97$[3].

The yields of each of the plots in the phosphoric acid series may now be calculated by the equation

$$Y=M-AR^x \tag{1}$$

as follows

Plot No.	x	R^x	AR^x	Calculated Y	Observed Y	e
13	0	1.00000	698.97	504.00	504	0
12	4	.19453	135.97	1,067.00	1,067	0
11	6	.08580	59.97	1,143.00	1,143	0
10	7	.05698	39.83	1,163.14	1,133	30.14
9	9	.02513	17.57	1,185.40	1,126	59.40
8	10	.01669	11.67	1,191.30	1,121	70.30
7	12	.00736	5.14	1,197.83	1,137	60.83

[3] In equation (1), M is the theoretical maximum yield (value of Y), while A is the theoretical maximum increase in yield from $x=0$; hence, if Y_0 represent the yield at $x=0$, $M=A+Y$.

The residuals (e) in the last column presumably show the decrease in yield due to earlier maturity from the heavier applications of phosphates. This is doubtless more than compensated by increase in quality, and consequently in price.

POTASH SERIES

(Plots 15 to 20)

The potash plots (last section of fig. 5) show neither the cumulative effect of large doses as the ammonia plots do, nor the gradual depletion on the lightly fertilized plots as the phosphoric acid plots do. The yields, however, are relatively irregular, and the values of M, A, and R calculated from them are less reliable than are those from the other series. In the absence of the trends above referred to, the 6-year average yield of each plot was used in the computations, the yields in 1925 being reduced to make the average that year comparable with the average of the first and third years.

The constants were evaluated by the author's new method, with the following result:

$$R=0.64364$$
$$A=492.61$$
$$M=1{,}224.85$$

In these computations 10 pounds of potash (K_2O) was used as the unit of x.

From the above values the yield of each plot may be calculated from the usual yield equation, as follows:

Plot No.	x	R^x	AR^x	Calculated Y	Observed Y	e
20	0	1.00000	492.61	732.24	731	1.24
19	2	.41427	204.07	1,020.78	1,021	−.22
18	3	.26664	131.35	1,093.50	1,110	−16.50
17	4	.17162	84.54	1,140.31	1,125	15.31
16	6	.07110	35.02	1,189.83	1,175	14.83
15	8	.02945	14.51	1,210.34	1,225	−14.66

Having worked out the constants of equation (1) for each of the fertilizer elements separately, the next step is to apply the results to equation (7), in which all three elements are variable. This is done in the following pages.

Data are now at hand for computing the quantities of available plant-food elements in the soil of this experimental field. These data, from the three preceding series, are:

Ammonia series: $M=1{,}323.44$, $R=0.69787$, and $A=436.02$.
Phosphoric acid series: $M=1{,}202.97$, $R=0.66412$, and $A=698.97$.
Potash series: $M=1{,}224.85$, $R=0.64364$, and $A=492.61$.

Substituting these values in equation (5), and remembering that the unit of each element is 10 pounds, we find that the values of q (the quantity available in the soil) for each of the series are

Ammonia series, 30.89 pounds NH_3.
Phosphoric acid series, 13.25 pounds P_2O_5.
Potash series 20.66 pounds K_2O.

ALL THREE VARIABLES TAKEN TOGETHER

The three values of A found above are the limiting values of Y, (1), when amomnia alone varies, and phosphoric acid and potash are held constant at 80 and 50 pounds per acre, respectively; (2), when

phosphoric acid varies and ammonia and potash remain constant at 30 and 50 pounds per acre, respectively; and so on.

It is necessary now to find the value of A which represents the limiting value of Y when all three of the fertilizer constituents vary. The computations involve finding the value of $(1-R^x)$ for many values of x. To save labor, a table of values of $(1-R^x)$ for all values of x likely to occur in such computations is appended. (Table 19). It is used in a manner similar to that in which a logarithmic table is used.[4] Values of x are given in the first column and the corresponding values of $1-R^x$ in the columns to the right. The figure in the second decimal place in the value of x is placed at the head of a column of values of $1-R^x$, as in a table of logarithms. The table is calculated for $R=0.8$. Hence it is necessary to convert the units of ammonia, phosphoric acid, and potash thus far used into new units that will give each R the value 0.8.

If R represent the ratio of any series of yield increments due to successive unit increases in a given growth factor, then the number, u, of such units that must be used as a new unit in order that R shall equal 0.8 is the value of u in the equation $R^u=0.8$.

Passing to logarithms, $u \log R = \log 0.8$, whence

$$u=\frac{\log 0.8}{\log R}=\frac{-0.0969100}{\log R} \tag{6}$$

The values found for R in the preceding work, with their logarithms, are

Ammonia series: $R=0.69787$; and $\log R=-0.1562255$.
Phosphoric acid series: $R=0.66412$; and $\log R=-0.1777534$.
Potash series: $R=0.64364$; and $\log R=-0.1913570$.

Substituting these values of $\log R$ in equation (6) above, we obtain the following values of u: Ammonia series, 0.6203; phosphoric acid series, 0.5452; potash series, 0.5064. Since the old units of each growth factor are 10 pounds each, the equivalent new units are respectively

Ammonia series, 6.203 pounds.
Phosphoric acid series, 5.452 pounds.
Potash series, 5.064 pounds.

The most general form of the yield equation, when all three fertilizer constituents vary, is

$$y=A(1-R^{n+a})\ (1-R^{p+b})\ (1-R^{k+c}) \tag{7}$$

The derivation of this equation is given later. The significance of the quantities involved is as follows:

y = yield per acre.

A = limit approached by y as a, b, and c increase.

R = the ratio of the series of increments in yield for successive unit increments in a, b, or c, the size of the unit in each case being such as to make $R=0.8$.

n, p, and k = the respective quantities, in the above units, of nitrogen (ammonia in the case under consideration), phosphoric acid, and potash available in the soil.

a, b, and c = the respective quantities of these three fertilizer elements in the fertilizer applied.

[4] The use of this table is explained on p. 60.

To use equation (7) it is necessary to express n, p, k, a, b, and c in terms of the new units mentioned above. To aid in doing this, some of the data developed in preceding pages are here brought together.

For n and a the new unit is 6.203 pounds of NH_3.
For p and b the new unit is 5.452 pounds of P_2O_5.
For k and c the new unit is 5.064 pounds of K_2O.
The value of n, 30.89 pounds, is 4.98 new units.
The value of p, 13.25 pounds, is 2.43 new units.
The value of k, 20.66 pounds, is 4.08 new units.

Table 4 shows in the first group of three columns the plant-food elements applied in fertilizer to each of Garner's plots, in units of 10 pounds (1 per cent of 1,000 pounds). In the next group the same quantities are shown in pounds (per acre, of course). In the third group these quantities are expressed in the new units, namely, units of the magnitude required to make the ratio (R) of each series equal 0.8.

TABLE 4.—*Plant food available on each plot in the tobacco experiments*

Plot No.	Plant food applied, in terms of—									Total available [1] (in new units)		
	Units of 10 pounds			Pounds			New units					
	NH_3, a	P_2O_5, b	K_2O, c	NH_3, a	P_2O_5, b	K_2O, c	NH_3, a	P_2O_5, b	K_2O, c	NH_3, $n+a$	P_2O_5, $p+b$	K_2O, $k+c$
1	5	8	5	50	80	50	8.06	14.67	9.87	13.04	17.10	13.95
2	4	8	5	40	80	50	6.45	14.67	9.87	11.43	17.10	13.95
3	3	8	5	30	80	50	4.84	14.67	9.87	9.82	17.10	13.95
4	2	8	5	20	80	50	3.22	14.67	9.87	8.20	17.10	13.95
5	0	8	5	0	80	50	0	14.67	9.87	4.98	17.10	13.95
6 [2]	0	0	0	0	0	0	0	0	0	4.98	2.43	4.08
7	3	12	5	30	120	50	4.84	22.01	9.87	9.82	24.44	13.95
8	3	10	5	30	100	50	4.84	18.34	9.87	9.82	20.77	13.95
9	3	9	5	30	90	50	4.84	16.51	9.87	9.82	18.94	13.95
10	3	7	5	30	70	50	4.84	12.84	9.87	9.82	15.27	13.95
11	3	6	5	30	60	50	4.84	11.01	9.87	9.82	13.44	13.95
12	3	4	5	30	40	50	4.84	7.34	9.87	9.82	9.77	13.95
13	3	0	5	30	0	50	4.84	0	9.87	9.82	2.43	13.95
14 [2]	0	0	0	0	0	0	0	0	0	4.98	2.43	4.08
15	3	8	8	30	80	80	4.84	14.67	15.80	9.82	17.10	19.88
16	3	8	6	30	80	60	4.84	14.67	11.85	9.82	17.10	15.93
17	3	8	4	30	80	40	4.84	14.67	7.90	9.82	17.10	11.98
18	3	8	3	30	80	30	4.84	14.67	5.92	9.82	17.10	10.00
19	3	8	2	30	80	20	4.84	14.67	3.95	9.82	17.10	8.03
20	3	8	0	30	80	0	4.84	14.67	0	9.82	17.10	4.08

[1] Quantity available in the soil plus quantity applied in fertilizer.
[2] Check plots; no fertilizer applied.

In the last group of three columns the numbers are obtained by adding the value of n, which is 4.98 in the new units, to each number in the a column of the preceding group, the value of p, or 2.43, to each number in the b column, and the value of k, or 4.08, to each number in the c column.

The last group of three columns thus shows the total quantity of each food element available to the crop on each of the 20 plots. It includes both the plant-food elements in fertilizers applied (a, b, c), and those available in the soil before the fertilizers were applied (n, p, k).

It is now possible by means of equation (7), Table 4, and Table 19, to find a value of the A of equation (7) for each of the 20 plots. In the case of plot 1, for instance, equation (7) becomes

$$y = A(1-R^{13.04})\ (1-R^{17.10})\ (1-R^{13.95}) \qquad (A)$$

the value of R being 0.8. From Table 19 it will be found that

$$1-R^{13.04}=0.94551$$
$$1-R^{17.10}=0.97798$$
$$1-R^{13.95}=0.95553$$

The calculated yield for this plot (p. 20) is 1,251.27 pounds. Substituting this value and the above values of the three parentheses in equation (A) above, transposing both members, and then dividing through by the parentheses

$$A=1{,}251.27/(0.94551)\ (0.97798)\ (0.95553)=1{,}416.15 \text{ pounds}$$

TABLE 5.—*Computation of the value of A for the plots of the tobacco experiments*

$$\left[A=\frac{\text{Calculated yield}}{\text{Product}}=\frac{y}{(1-R^{n+a})\ (1-R^{p+b})\ (1-R^{k+c})}.\ \text{Data of Table 4}\right]$$

Plot No.	Calculated yield,[1] y (pounds)	$1-R^{n+a}$ [2]	$1-R^{p+b}$ [2]	$1-R^{k+c}$ [2]	Product	A (pounds)
1	1, 251. 27	0. 94551	0. 97798	0. 95553	0. 88357	1, 416. 15
2	1, 220. 02	. 92196	. 97798	. 95553	. 85156	1, 416. 06
3	1, 175. 25	. 88823	. 97798	. 95553	. 83004	1, 415. 90
4	1, 111. 09	. 83991	. 97798	95553	. 78489	1, 415. 60
5	887. 42	. 67085	. 97798	. 95553	. 62690	1, 415. 57
6		. 67085	. 41855	. 59765	. 16781	
Average						1, 415. 86
7	1, 197. 83	. 88823	. 99572	. 95553	. 84510	1, 417. 38
8	1, 191. 30	. 88823	. 99029	. 95553	. 84049	1, 417. 39
9	1, 185. 40	. 88823	. 98539	. 95553	. 83633	1, 417. 38
10	1, 163. 14	. 88823	. 96687	. 95553	. 82061	1, 417. 41
11	1, 143. 00	. 88823	. 95017	. 95553	. 80644	1, 417. 34
12	1, 067. 00	. 88823	. 88697	. 95553	. 75280	1, 417. 38
13	504. 00	. 88823	. 41855	. 95553	. 35524	1, 418. 76
14		. 67085	. 41855	. 59765	. 16781	
Average						1, 417. 58
15	1, 210. 34	. 88823	. 97798	. 98816	. 85839	1, 410. 01
16	1, 189. 83	. 88823	. 97798	. 97141	. 84384	1, 410. 02
17	1, 140. 31	. 88823	. 97798	. 93097	. 80871	1, 410. 04
18	1, 093. 50	. 88823	. 97798	. 89263	. 77540	1, 410. 24
19	1, 020. 73	. 88823	. 97798	. 83335	. 72391	1, 410. 09
20	732. 24	. 88823	. 97798	. 59765	. 51916	1, 410. 43
Average						1, 410. 14
Grand average						1, 414. 53

[1] These yields are those previously calculated. See text for each series of plots.
[2] This is $(1-R^x)$ for the series. See last group of columns of Table 4 for the several values of x to be used in entering Table 19.

In a similar manner the value of A for each of the remaining plots was obtained, the results for all except the two check plots being shown in Table 5.

The slight variations in the value of A in the ammonia series, from 1,415.57 to 1,416.15, are due to omission of decimals in the preceding computations. A similar remark applies to the A of the phosphate series, plots 7 to 13, and to that in the potash series, plots 15 to 20.

There are thus three values of A, namely—

From the ammonia series	1, 415. 86
From the phosphate series	1, 417. 58
From the potash series	1, 410. 14

the extreme difference between which is about 0.5 per cent of their magnitude.

In arriving at each of these values, three factors were multiplied together. In each case, one factor is derived from data wholly independent of the others. The fact that the three values agree so closely indicates a high degree of fitness in the theory of the yield equation

$$y = A\ (1 - R^{n+a})\ (1 - R^{p+b})\ (1 - R^{k+c}) \qquad (7)$$

from which the values are derived.

FINAL CALCULATED YIELDS

Using the average of the three values of A in the above equation, and multiplying this by each of the "products" in the next to last column, Table 5, the final calculated yield of each of the experimental plots is obtained. In Table 6 these are compared with the observed yields.

TABLE 6.—*Final calculated yield of each plot compared with the observed yield*

Plot No.	Calculated Y	Observed Y	e	100 e/Y	Plot No.	Calculated Y	Observed Y	e	100 e/Y
1	1,250	1,231	19	1.5	11	1,141	1,143	−2	−.2
2	1,219	1,248	−29	−2.3	12	1,065	1,067	−2	−.2
3	1,174	1,181	−7	−.6	13	502	504	−2	−.4
4	1,110	1,095	15	1.4	14 [1]				
5	887	890	−3	−.3	15	1,214	1,225	−11	−.9
6 [1]					16	1,194	1,175	19	1.6
7	1,195	1,137	58	5.1	17	1,144	1,125	19	1.7
8	1,189	1,121	68	6.1	18	1,097	1,110	−13	−1.2
9	1,183	1,126	57	5.1	19	1,024	1,021	3	.3
10	1,161	1,133	28	2.5	20	734	731	3	.4

[1] Check plot.

The column headed e in Table 6 shows the difference between the final calculated yields and the observed yields. In the next column these differences are expressed as percentages of the observed yields.

Plots 7 to 10 of the phosphoric acid series show what is presumably the reduction in yield due to the effect of large doses of phosphate, a reduction probably much more than compensated for by increase in quality of product (tobacco). Thus, on plot 7 the calculated yield is 58 pounds more than the observed yield. This is presumably the reduction in yield due to the earlier maturity caused by the large application of phosphoric acid.

Of the remaining plots, 13 show residuals of less than 2 per cent, 8 of them less than 1 per cent. The remaining residual is 2.3 per cent.

This must be regarded as nothing less than remarkably close agreement between calculated and observed yields.

YIELD OF CHECK PLOTS

Two plots, Nos. 6 and 14, received no fertilizer applications. The yield calculated for these plots by the yield formula is only 238 pounds, whereas the actual average yield for the last three years on plot 6 was 503 pounds, and on plot 14, 498 pounds. The reason for this discrepancy is that the lower part of the phosphate curve represents yield increases due in part to current applications and in part to varying rates of phosphate exhaustion. Extrapolations down-

ward by this curve do not give correct results. But these disturbing conditions do not exist for the upper part of this curve, so that extrapolation upwards should give correct results.

If the soil had not been so fully stocked with available phosphates at the beginning of the experiment, and if the first-year results alone had been used in the computations, then the yield of the check plots could have been calculated by the yield equation.

A hint as to the rate of phosphate exhaustion on plot 13, which received no phosphates, but did receive ammonia at the rate of 30 pounds and potash at the rate of 50 pounds per acre, is seen in Figure 6, where a comparison is given between the yields on plot 13, plot 11, which received phosphoric acid at the rate of 60 pounds per acre, along with 30 pounds of ammonia and 50 pounds of potash, and plot 14, which received no fertilizers.

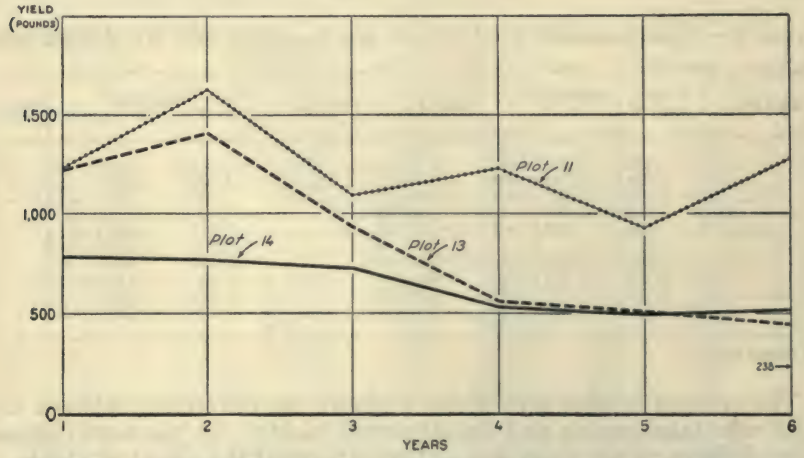


FIGURE 6.—YIELDS OF TOBACCO ON THREE PLOTS IN THE PHOSPHORIC ACID SERIES

Plot 13 gives a hint as to the rate of exhaustion of phosphoric acid. Had it received no ammonia or potash, its yield in the sixth year presumably would have been 238 pounds, indicated by the arrow. Plot 14 received no fertilizer. Plot 11 received complete fertilizer, 60 pounds phosphoric acid along with 30 pounds of ammonia and 50 pounds of potash.

By the fourth year the yield on plot 13 had fallen about to the level of that on plot 14, and remained there during the remainder of the period. Had it received no ammonia or potash the last three years, its yield the last year would presumably have been 238 pounds, indicated by the arrow.

The exhaustion of phosphates in the case of plot 13 was presumably much greater than in the case of plot 14, for during the early years of the experiment the yields on plot 13 were much greater than on plot 14, neither plot having received any phosphates.

While, as stated above, the lower part of the phosphate curve (middle section, fig. 5, at bottom) does not give a true picture because of the nature of the data on which it is based, the same can not be said of the other curves or of the upper part of this one. The upper part of each of the three curves presents what is presumably a true picture. This being the case, extrapolation upwards by means of the yield formula should give reliable results. The close agreement of

the maximum possible yields for the three series tends to confirm this statement.

For a series of experiments planned as suggested later in this bulletin, and carried out on a uniform soil, the equation, if the theory on which it is based is true, should enable one to extrapolate either upward or downward indefinitely. The formula, of course, ceases to apply when the fertilizer application becomes so large as to be injurious to the crop. The effect of phosphates in hastening maturity may also cause departures of calculated from observed yields. The curve therefore offers a means of determining the reduction in yield due to the earlier maturity.

OPTIMUM FERTILIZER FORMULAS

A method of determining the most profitable quantity of ammonia (NH_3) and of potash (K_2O) to use with any given quantity of phosphoric acid (P_2O_5) follows.

Certain of the items of cost per unit of product are proportional to area. These include plowing, preparation of seed bed, planting, tillage, and sometimes part of the work of harvesting. Thus, in the case of sugar beets or potatoes, the cost of running the digger is proportional to acreage.

It is true that the amount of work done in preparing seed bed and in tillage, spraying, etc., may vary widely, and the amount and character of such work does affect the yield; but on most farms there are fixed standards for such tasks, and the work done is strictly proportional to acreage. The formulas developed below apply only to cases in which work of this kind is standardized and varies with acreage.

Certain unit costs vary strictly with yield per acre. Thus, grading, sacking or crating, hauling to storage or to market, and the like depend on yield, not on acreage.

Certain other costs are intermediate in character between the above two classes. Thus, in husking corn, for instance, the amount of labor required depends partly on area and partly on yield per acre. It costs slightly more per bushel to husk a field of corn yielding 40 bushels per acre than one yielding 60 or 80 bushels.

In considering these intermediate items from the standpoint of optimum applications of the various fertilizer ingredients it should be remembered that, in most cases, only slight variations in yield are involved. Thus, it may be a question whether a fertilizer application necessary to obtain a yield of 79 bushels or 80 bushels of corn would be most profitable. The variation in cost per bushel as between these yields for the one item of husking is too small to measure. There will therefore be no serious error if such costs are regarded as varying with yield. This point is discussed later in some detail.

In the case of some crops there are other factors of cost that vary partly with area and partly with yield. A heavy crop of sugarcane, for instance, requires less tillage and weeding than a light crop (*8*). Even in this case, however, when the question is between a yield of 19 tons and one of 20 tons, the difference in cost of this item is slight, and may be neglected without serious error.

In what follows the argument proceeds as if all items of cost may be regarded as varying with either area or yield per acre. In some cases this will involve a small degree of error, but not sufficient to

vitiate the results, as will be seen later. In the case of sugar beets, where the harvesting is done by contract, at so much per acre, which is a common practice, the error does not enter.

In the subsequent discussion use is made of the following symbols:

a=units of available ammonia (NH_3) in fertilizer applied.
b=units of available phosphoric acid (P_2O_5) in fertilizer.
c=units of available potash (K_2O) in fertilizer.
$a'=a+q'$.
$b'=b+q''$.
$c'=c+q'''$.
C=sum of acre costs proportional to area.
H=costs per unit proportional to yield (the harvesting and marketing costs).
k=units of available potash in an acre of soil.
m=0.434,2945,–the modulus of the common system of logarithms.
M=maximum limit of y.
n=units of available ammonia in an acre of soil.
p=units of available phosphoric acid in an acre of soil.
P=profit per acre.
q'=units of NH_3 absorbed per acre.
q''=units of P_2O_5 absorbed per acre.
q'''=units of K_2O absorbed per acre.
$Q=m/v\ M(-\log R)$.
r'=cost of a unit of ammonia (including cost of application).
r''=cost of a unit of phosphoric acid (including cost of application).
r'''=cost of a unit of potash.
R=ratio of series of increments in y due to successive unit increments of nitrogen, phosphoric acid, or potash, =0.8.
$R'=R^{x_1}=R^{n+a}$.
$R''=R^{x_2}=R^{p+b}$.
$R'''=R^{x_3}=R^{k+c}$.
$s=r'a'+r''b'+r'''c'$=cost of fertilizer per acre.
$s'=r'R''+r''(1-R'')$.
$s'''=r'''R''+r''(1-R'')$.
$S'=1-R'$.
$S''=1-R''$.
$S'''=1-R'''$.
$v=V-H$=value of a unit of product less unit costs proportional to yield (harvesting and marketing costs).
V=value at market of a unit of product.
x'=units of NH_3 per acre=$n+a$.
x''=units of P_2O_5 per acre=$p+b$.
x'''=units of K_2O per acre=$k+c$.
y=yield per acre.

Let P=profit per acre. Then

$$\begin{aligned} P &= Vy-Hy-r'a'-r''b'-r'''c'-C \\ &= vy-r'a'-r''b'-r'''c'-C \end{aligned} \qquad (A)$$

Considering first the most profitable application of ammonia, the problem is to find the value of a' that will render P a maximum. This value is obtained by placing equal to zero the partial derivative of P with respect to a'.

Differentiating (A) with respect to a', and noting that, since $a'=a+q'$, $da'=da$,

$$\frac{dP}{da}=v\frac{dy}{da}-r'=0 \qquad (B)$$

Now $y=MS'S''S'''$, in which M has the same significance as the A of formula (7) on page 22. Substituting this value of y in (B) and

performing the indicated differentiation, the result may be reduced to the form shown in equation (C) below.

$$R'S''S'''=\frac{mr'}{vM(-\log R)} \tag{C}$$

in which $m=0.4342945$, the modulus of the common system of logarithms.
Letting $Q=m/vM(-\log R)$, this may be written

$$R'S''S'''=Qr' \tag{D}$$

The corresponding equations for P_2O_5 and K_2O, obtained in a similar manner, are

$$S'R''S'''=Qr'' \tag{E}$$

and

$$S'S''R'''=Qr''' \tag{F}$$ (8)

To solve these equations for R' and R''' in terms of R'', multiply (D) by (S'), (E) by (S''), and (F) by (S'''); and divide (D) by R', (E) by R'', and (F) by R'''. This gives

$$S'S''S'''=Qr'(S')/R' \tag{G}$$
$$S'S''S'''=Qr''(S'')/R'' \tag{H}$$
$$S'S''S'''=Qr'''(S''')/R''' \tag{I}$$

Equating the second members of (G) and (H),

$$Qr'(S')/R'=Qr''(S'')/R''$$

Multiplying through by $R'R''$, and dividing through by Q,

$$r'R''(S')=r''R'(S'')$$

Restoring the values of S' and S'',

$$r'R''-r'R'R''=r''R'-r''R'R''$$

Transposing, and changing signs

$$r'R'R''+r''R'-r''R'R''=r'R''$$

Factoring, $R'(r'R''+r''-r''R'')=r'R''$.

Dividing,

$$R'=\frac{r'R''}{r'R''+r''(1-R'')}=\frac{r'R''}{s'} \tag{9}$$

Equating the second members of (H) and (I),

$$Qr''\ (S'')/R''=Qr'''(S''')/R'''$$

Proceeding as in the case of R', the value of R''' is found to be

$$R'''=\frac{r'''R''}{r'''R''+r''(1-R'')}=\frac{r'''R''}{s'''} \tag{10}$$

Equations (9) and (10) now permit the determination of the most profitable quantities of NH_3 and K_2O to use with any quantity of P_2O_5 within the toxic limit of these substances. The data required are as follows:

$r'=\$1.088=6.203$ pounds of NH_3 at $\$0.1754=$cost of a unit of NH_3.
$r''=\$0.393=5.452$ pounds of P_2O_5 at $\$0.0720=$cost of a unit of P_2O_5.

r'''=\$0.385=5.064 pounds of K_2O at \$0.0760=cost of a unit of K_2O.
u_1=a unit of NH_3=6.203 pounds.
u_2=a unit of P_2O_5=5.452 pounds.
u_3=a unit of K_2O=5.064 pounds.
n=4.98;
p=2.43;
k=4.08.

The values are worked out for several cases in Table 7, the procedure of which is illustrated by the column headed "For b=20 pounds"; that is, if 20 pounds of phosphoric acid, P_2O_5 are to be used, what are the corresponding most profitable quantities of ammonia, NH_3, and of potash, K_2O, to use?

Convert pounds of P_2O_5 into units: $20 \div 5.452$, b	=	3.67
Write p, in units	=	2.43
Add these, giving the x of the yield equations, or $x''=p+b$	=	6.10
In Table 19 find $(1-R^x)$ at 6.10, or $1-R''$	=	.74364
whence, subtracting from 1, R''	=	.25636
Multiply R'' by r', which is 1.088, giving $r'R''$	=	.27892
Multiply $(1-R'')$ by r'', which is 0.393, giving $r''(1-R'')$	=	.29225
Add $r'R''$ to $r''(1-R'')$ giving s'	=	.57117
Dividing $r'R''$ by s' gives R'	=	.48833
whence, subtracting from 1, $1-R'$, or S'	=	.51167
From Table 19 read the value of $1-R'$, which is x' or $n+a$ units	=	3.21
whence, by subtraction (n=4.98) a, in units	=	−1.77
Converting units to pounds, a in pounds	=	−11.0

Since a is negative, it does not pay to use any ammonia, NH_3, in this case when only 20 pounds of phosphoric acid are applied.

The correct quantity of potash is calculated in the lower section of the table. The reader should now be able to follow the procedure indicated. When 20 pounds of phosphoric acid are used, 10.6 pounds of potash are indicated as the most profitable application.

TABLE 7.—*Computation of most profitable quantities of ammonia and of potash to use with given quantities of phosphoric acid*

Step in computation [1]	For b=5 pounds	For b=10 pounds	For b=20 pounds	For b=40 pounds	For b=60 pounds	For b=80 pounds	For b=100 pounds	For b=120 pounds
b, in units	0.92000	1.83	3.67	7.34	11.01	14.67	18.34	22.01
$b+p$ (p=2.43)	3.35000	4.26	6.10	9.77	13.44	17.10	20.77	24.44
$1-R''$	.52647	.61349	.74364	.88697	.95011	.97798	.99029	.99572
R''	.47353	.38651	.25636	.11303	.04989	.02202	.00971	.00428
r' R'' (r'=1.088)	.51520	.42052	.27892	.12298	.05428	.02396	.01056	.00466
r'' $(1-R'')$	.20690	.24110	.29225	.34858	.37339	.38435	.38918	.39132
s' $[=r'R''+r''(1-R'')]$	.72210	.66162	.57117	.47156	.42767	.40831	.39974	.39598
R' $(r'R''/s')$	.71346	.63559	.48833	.26079	.12692	.05868	.02642	.01177
$1-R'$	.28654	.36441	.51167	.73821	.87308	.94132	.97358	.98823
$n+a$, $=x'$, in units	1.51	2.03	3.21	6.02	9.25	12.71	16.28	19.91
a, in units	−3.47	−2.95	−1.77	1.04	4.27	7.73	11.30	14.93
a, in pounds	−21.5	−18.3	−11.0	6.5	26.5	47.9	70.1	92.6
r''' R''	.18231	.14881	.09870	.04352	.01928	.00848	.00374	.00165
s''' $[=r'''R''+r''(1-R'')]$	.38921	.38991	.39095	.39210	.39260	.39283	.39292	.39297
R''' $(=r'''R''/s''')$	.46841	.38165	.25246	.11099	.04893	.02159	.00952	.00420
$1-R'''$	.53159	.61835	.74754	.88901	.95107	.97841	.99048	.99580
$k+c$, $=x'''$, in units	3.40	4.32	6.17	9.86	13.52	17.19	20.86	24.52
c, in units	−.68	.24	2.09	5.78	9.44	13.11	16.78	20.44
c, in pounds	−3.4	1.2	10.6	29.3	47.8	66.4	85.0	103.5

[1] Find in the previous work or in Table 19 or compute as indicated in text.

Figure 7 was constructed from data in Table 7 and additional data similarily calculated. The abscissas of the figure are pounds of P_2O_5 per acre. For any one abscissa, the ordinates of the two curves show the quantities, in pounds per acre, of NH_3 and K_2O to use for greatest

profit. Thus, at 70 pounds of P_2O_5 the ordinate of the NH_3 curve is 37.3; of the K_2O curve, 57. The exact quantities of NH_3 and K_2O to use with any quantity of P_2O_5 are easily calculated by the method of Table 7.

The method of converting quantities of fertilizer constituents per acre into fertilizer formulas may be illustrated from the data in any column of Table 7. In the column headed "For $b=60$ pounds" for instance, it is shown that the optimum quantities of ammonia and

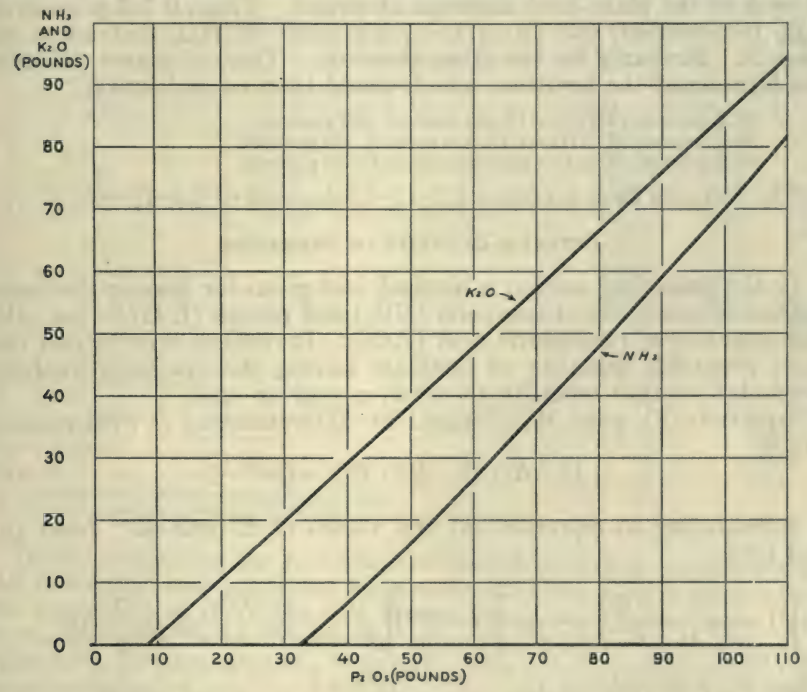


FIGURE 7.—QUANTITY OF AMMONIA AND OF POTASH ASSOCIATED WITH PHOSPHORIC ACID IN THE OPTIMUM FERTILIZER ANALYSIS FOR TOBACCO AT TIFTON, GA.

The computation showed the optimum fertilizer formula for tobacco in this series of experiments. With this chart the optimum quantities of ammonia and potash to use with any desired application of phosphoric acid may be read directly. Thus, ammonia will not pay if less than 33 pounds of P_2O_5 are used.

potash to use with 60 pounds of phosphoric acid in this case (tobacco at Tifton, Ga.) are

Phosphoric acid	60 pounds
Ammonia	26.5 pounds
Potash	47.8 pounds

To find the quantity and analysis (formula) of fertilizer containing these quantities of the three constituents, with, say, 12 per cent of phosphoric acid, proceed as follows:

60 pounds of $P_2O_5=12.0$ per cent of 500 pounds.
26.5 pounds of $NH_3=5.3$ per cent of 500 pounds.
47.8 pounds of $K_2O=9.6$ per cent of 500 pounds.

Hence in this case 500 pounds of a 5.3–12–9.6 fertilizer will contain plant-food elements in the right proportion to make the profit greatest from a fertilizer containing 60 pounds of phosphoric acid.

The foregoing problem has been worked out on the assumption that none of the plant food in fertilizers is absorbed, or occluded, by the soil. When the phenomenon of absorption is present, it is allowed for at this point by adding to the 60 pounds of P_2O_5, 26.5 pounds of NH_3, and 47.8 pounds of K_2O above, the quantity, in pounds per acre, of each of the plant-food elements absorbed. Thus, if 7.2 pounds of P_2O_5 is absorbed, use $60+7.2=67.2$ pounds of P_2O_5 instead of 60 pounds. Similarly for the other elements. This, of course, changes the formula of the fertilizer, which would then be as follows:

67.2 pounds of P_2O_5=12 per cent of 560 pounds.
26.5 pounds of NH_3=4.73 per cent of 560 pounds.
47.8 pounds of K_2O=8.54 per cent of 560 pounds.

The formula then becomes 4.7–12–8.5 instead of 5.3–12–9.6.

OPTIMUM QUANTITY OF FERTILIZER

In the preceding section a method was given for finding the most profitable quantities of ammonia (NH_3) and potash (K_2O) to use with any quantity of phosphoric acid (P_2O_5). It remains now to find the most profitable quantity of fertilizer having the optimum analysis (formula) for that quantity to use in any given case.

Equation (8), page 29, obtained by differentiating P with respect to c is

$$(1-R')\ (1-R'')\ R'''=Qr''' \tag{8}$$

Substituting in equation (8) the values of R' and R''' from (9) and (10),

$$\left[1-\frac{r'R''}{r''\ (1-R'')+r'R''}\right][1-R'']\left[\frac{r'''R''}{r''\ (1-R'')+r'''R''}\right]=Qr''',$$

which may be reduced to

$$\frac{r''S''\cdot R''S''}{s'\cdot s'''}-Q=O \tag{11}$$

This is an equation of the third degree in R'', best solved by the method of trial and error. The work involved in solving it for a specific case is outlined later.

Being of the third degree, the equation has three roots. One of them is imaginary, another is negative, while the third root represents a maximum value of P (profit per acre). It is this last value that is sought.

Let T represent the fraction in equation (11); then

$$T-Q=O \tag{12}$$

The problem now is to solve equation (12).

The solution of this equation is given in Table 8. Note that $R''=R^{p+b}$, in which $R=0.8$, $p=2.43$ (units of 5.452 pounds of P_2O_5), and b is the quantity of P_2O_5 applied in fertilizer, in units of 5.452

pounds. Assigning b a value in pounds, and then reducing this value to units, the value of R'' is fixed.

TABLE 8.—*Computation of T of equation (12) for the tobacco experiments* [1]

$$T=\frac{r''(1-R'')\cdot r'''(1-R')}{[r'R''+r''(1-R'')][r'''R''+r''(1-R'')]}$$ value of Q is 0.02263

[The values of the quantities are those previously used in this demonstration]

	Step in computation [2]	First trial	Second trial	Third trial
1	b, in pounds	101.1	101.2	101.3
2	b, in units	18.54	18.56	18.58
3	$p+b$, in units	20.97	20.99	21.01
4	$1-R''$ (Table 19)	.99071	.99075	.99080
5	R''	.00929	.00925	.00920
6	$r''(1-R'')$	.38935	.38936	.38938
7	$R''(1-R'')$	.00920	.00916	.00912
8	Step 6×step 7	.00358	.00357	.00355
9	$r'R''$	.01011	.01006	.01001
10	$r'''R''$	.00358	.00356	.00354
11	$r''(1-R'')+r'R''$	.39946	.39942	.39939
12	$r''(1-R'')+r'''R''$	.39293	.39292	.39292
13	Step 11×step 12	.15696	.15694	.15693
14	T=step 8÷step 13	.02281	.02275	.02263
15	R'=step 9÷step 11			.02506
16	$1-R'$			.97494
17	$n+a$, in units			16.52
18	a, in units			11.54
19	a, in pounds			71.6
20	R'''=step 10÷step 12			.00901
21	$1-R'''$			.99099
22	$k+c$, in units			21.105
23	c, in units			17.025
24	c, in pounds			86.2

[1] The procedure, however, is general in application.
[2] Find in the previous work or in Table 19 or compute as indicated.

Before explaining the procedure of the table, it may be stated that the value of T was calculated for a series of values of b (in pounds) by the procedure of the table and Figure 8 was constructed from data thus obtained. In that figure the value of T may be read off for any value of b (in pounds) from 0 to 120. The solution of equation (12) involves finding a value of b for which $T=Q$, indicated at X in Figure 8. The value of Q is $m/vA(-\log R)$ (p. 28). Since $m=0.4342945$, and for the special case under consideration (tobacco at Tifton, Ga.) $v=0.14$, $A=1414.53$ (p. 24), and $-\log R=0.0969100$; the value of Q is 0.02263. Figure 8 shows that $T=Q$ at about $b=101$. This gives a starting point for Table 8, the procedure of which is like that of Table 7. The first value of b tried in the table was 101; the second was 101.1, the column calculated on the basis of $b=101$ being omitted to economize space. For $b=101.1$, the resulting value of T is 0.02281, a little too large. The next trial was for $b=101.2$, giving $T=0.02275$. The last trial, with $b=101.3$, gave $T=0.02263$, which is exactly the value sought.

When the value of b that renders $T=Q$ is found, the proper quantities of ammonia and of potash to use with that quantity of phosphoric acid may be computed as indicated in the lower part of Table 8, steps 15 to 24. Thus it appears that the application per acre giving the maximum profit in this case is

NH_3	71.6 pounds.
P_2O_5	101.3 pounds.
K_2O	86.2 pounds.

Conversion of these quantities of plant foods into terms of a fertilizer is accomplished by deciding on some percentage of one of them, and computing the associated percentages of the others. Thus, if the fertilizer to be used is based on 12 per cent of phosphoric acid, 844.2 pounds of fertilizer will be needed in this case, for $101.3 \div 0.12 = 844.2$. This quantity of fertilizer must have 8.5 per cent of ammonia to furnish 71.6 pounds ($71.6 \div 8.442$), and 10.2 per cent of potash to furnish 86.2 pounds ($86.2 \div 8.442$). Hence 844.2 pounds of 8.5–12–10.2 fertilizer will give the largest profit per acre in this case.

If the phenomenon of plant-food absorption is present, it is taken care of at this point by adding to the above 71.6 pounds of NH_3, 101.3 pounds of P_2O_5, and 86.2 pounds of K_2O, the quantity in pounds per acre, of each element absorbed. This modifies the formula, as well as the quantity per acre of fertilizer to apply. The profit per acre is reduced by the cost of the plant-food elements absorbed.

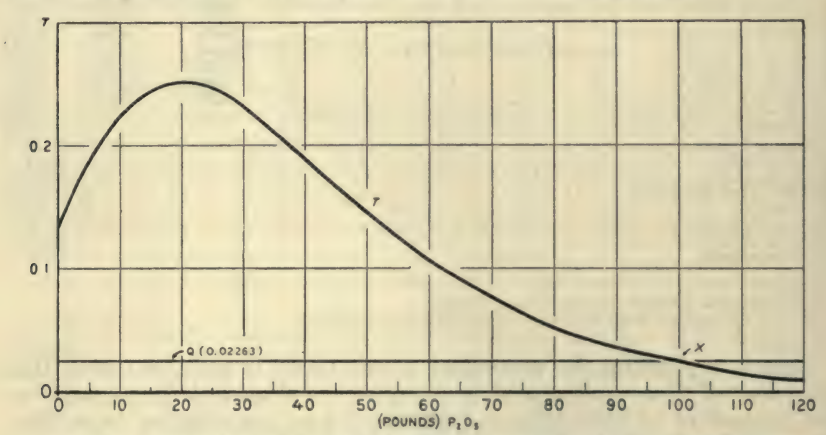


FIGURE 8.—VALUE OF *T* FOR DIFFERENT APPLICATIONS OF PHOSPHORIC ACID IN THE TOBACCO EXPERIMENTS AT TIFTON, GA.

As developed in the text, the point of intersection, *X*, at which *T* equals *Q*, shows the quantity of phosphoric acid per acre to use for greatest profit per acre for tobacco at Tifton, Ga. This quantity varies for different crops and for different soils. The quantities of ammonia and potash to be applied with this quantity of phosphoric acid are found directly from Figure 7, or computed from Table 8.

If the fertilizer is to contain 10 per cent of P_2O_5, then

101.3=10 per cent of 1,013 pounds.
71.6=7.1 per cent of 1,013 pounds.
86.2=8.5 per cent of 1,013 pounds.

That is, 1,013 pounds of a 7.1–10–8.5 fertilizer is most profitable. These results do not take into consideration the effect of heavy applications of phosphoric acid in hastening maturity of the crop, with resulting increase in quality, and presumably decrease in yield. They are therefore only approximate in the case considered. This difficulty does not arise in cases in which phosphoric acid does not have the effects mentioned.

The item of harvesting.—It has already been pointed out that it costs slightly less per pound to harvest a crop when the acre yield is large than when it is small. Thus, it should cost slightly less per pound to harvest a tobacco crop yielding 1,200 pounds per acre than one yielding 1,000 pounds.

In the case of tobacco, the one item that may vary in this manner is that of cutting and hauling the crop to the barn. In the preceding computations this variation was ignored.

To find what effect such variation may have on the results of the computations, note that, in the case of tobacco, the total cost of this item is ordinarily about 1.2 cents per pound. Suppose the item decreases to 1 cent because of the larger yield from adequate applications of fertilizer. This would change the value of v used in the computations from \$0.14 to \$0.142. Since $Q=m/vA\ (-\log R)$, this change in v reduces the value of Q from 0.02263 to 0.02195. The corresponding value of T, arrived at by the procedure of Table 8, is obtained when a, b, and c have the values shown below. The values of a, b, and c when $v=\$0.14$ are shown for comparison, as are also the yields corresponding to these fertilizer combinations.

$v=$	\$0.14	\$0.142.
$a=$	71.6	74.4 pounds of NH_3.
$b=$	101.3	102.0 pounds of P_2O_5.
$c=$	86.2	86.8 pounds of K_2O.
Optimum $y=$	1,353.86	1,354.08 pounds of tobacco per acre.

It is obvious that an increase in yield amounting to 1,354.08 − 1,353.86 = 0.22 pound could not measurably affect the cost per pound of harvesting. Hence the inaccuracy due to changing cost per pound of harvesting is negligible, and the results arrived at are dependable when the experimental data are adequate and there are no complications due to effect of the fertilizer on quality of product or date of maturity of the crop.

Effect of market price.—In the formulas, v is the value per pound of crop product less cost of harvesting and marketing. It has been assumed in the computations that $v=14$ cents in the case under consideration. The magnitude of v affects the results because of the presence of v as a factor in the denominator of Q, to which T should be equal. The values of $Q=\frac{0.003168}{v}$, for several values of v are:

v	$Q(=T)$
\$0. 10	0. 03168
\$0. 12	. 02640
\$0. 14	. 02263
\$0. 16	. 01980

The corresponding values of b, read from the curve of Figure 8, and of a and c read from Figure 7, are:

When v is \$0.10, b is 94.0 pounds, a is 63.5 pounds, and c is 79.0 pounds.
When v is \$0.12, b is 99.5 pounds, a is 69.5 pounds, and c is 84.5 pounds.
When v is \$0.14, b is 101.0 pounds, a is 71.5 pounds, and c is 86.0 pounds.
When v is \$0.16, b is 102.5 pounds, a is 73.0 pounds, and c is 87.5 pounds.

Converting these into fertilizer containing 10 per cent of P_2O_5:

$v=$\$0.10	94.0 pounds P_2O_5=10 per cent of 940 pounds.
	63.5 pounds NH_3=6.8 per cent of 940 pounds.
	79.0 pounds K_2O=8.4 per cent of 940 pounds.
$v=$\$0.12	99.5 pounds P_2O_5=10 per cent of 995 pounds.
	69.5 pounds NH_3=7 per cent of 995 pounds.
	84.5 pounds K_2O=8.5 per cent of 995 pounds.
$v=$\$0.14	101.0 pounds P_2O_5=10 per cent of 1,010 pounds.
	71.5 pounds NH_3=7.1 per cent of 1,010 pounds.
	86.0 pounds K_2O=8.5 per cent of 1,010 pounds.
$v=$\$0.16	102.5 pounds P_2O_5=10 per cent of 1,025 pounds.
	73.0 pounds NH_3=7.1 per cent of 1,025 pounds.
	87.5 pounds K_2O=8.5 per cent of 1,025 pounds.

These results may be summarized thus:

v	Most profitable fertilizer application
$0.10	940 pounds of 6.8–10–8.4 goods.
$0.12	995 pounds of 7.0–10–8.5 goods.
$0.14	1,010 pounds of 7.1–10–8.5 goods.

From this the conclusion appears to be justified that, with a range in price of tobacco from 10 to 16 cents a pound (market price less cost of harvesting and marketing), the standard application of fertilizer to tobacco at Tifton, Ga., should be from 900 to 1,000 pounds of about 7–10–8.5 fertilizer.

As before stated, this does not take into account the effect of heavy applications of P_2O_5 in hastening the maturity of the crop, and consequently increasing the quality of the product.

In spite of the limitations just mentioned, these results should be of value in arriving at correct fertilizer practice for the locality concerned.

OPTIMUM ACREAGE TO WHICH TO APPLY FERTILIZER COSTING A FIXED AMOUNT

Occasions not infrequently arise in which farmers for one reason or another are unable to procure as much fertilizer as they would like to use. It is therefore desirable to have formulas that make it possible to determine the optimum acreage to which a given amount (value) of fertilizer should be applied. In working out these formulas the following symbols are employed:

a=units of available NH_3 in fertilizer.
b=units of available P_2O_5 in fertilizer.
c=units of available K_2O in fertilizer.
$a'=a+q'$.
$b'=b+q''$.
$c'=c+q'''$.
g=optimum acreage.
C=sum of costs proportional to area other than fertilizer.
K=total cost of fertilizer.
k=units of available K_2O in an acre of soil.
$\text{Log}_e R$=natural logarithm of $R=-0.223144$.
M=upper limiting value of y.
n=units of available NH_3 in an acre of soil.
p=units of available P_2O_5 in an acre of soil.
p'=profit from an acre of the crop.
$P=gp'$=profit from the entire crop.
q'=units of NH_3 absorbed by an acre of soil.
q''=units of P_2O_5 absorbed by an acre of soil.
q'''=units of K_2O absorbed by an acre of soil.
r'=cost of a unit of NH_3.
r''=cost of a unit of P_2O_5.
r'''=cost of a unit of K_2O.
$R=0.8$.
$R'=R^{n+a}$.
$R''=R^{p+b}$.
$R'''=R^{k+c}$.
$s=r'a'+r''b'+r'''c'$, cost of fertilizer per acre.
$s'=r'R''+r''(1-R'')$.
$s'''=r'''R''+r''(1-R'')$.
$S'=1-R'$.
$S''=1-R''$.
$S'''=1-R'''$.
v=value of a unit of crop product less cost of harvesting and marketing.
y=yield per acre.
y_0=yield per acre when no fertilizer is applied.

Three cases are to be considered.

CASE 1. Only the acreage to be planted that will give a maximum profit from the crop.

The profit per acre is expressed by the formula

$$p' = vy - \frac{K}{g} - C$$

The profit on the entire crop is

$$P = gp' = gvy - K - gC \qquad \text{(A)}$$

The acreage to be planted, g, equals the total cost of the fertilizer divided by the amount applied per acre; that is, $g = K/(r'a' + r''b' + r'''c') = K/s$. The yield per acre is $y = MS'S''S'''$.

Substituting these values of y and g in equation (A),

$$P = \frac{KvMS'S''S''' - KC}{s} - K \qquad \text{(B)}$$

To obtain the values of a, b, and c that render P a maximum differentiate equation (B) with respect to a, then with respect to b, and then with respect to c, and place each of the resulting derivatives equal to zero. When this is done the three resulting equations are:

$$\text{Log}_e RsR'S''S''' + r'S'S''S''' = \frac{r'C}{vM} \qquad \text{(C)}$$

$$\text{Log}_e RsS'R''S''' + r''S'S''S''' = \frac{r''C}{vM} \qquad \text{(D)}$$

$$\text{Log}_e RsS'S''R''' + r'''S'S''S''' = \frac{r'''C}{vM} \qquad \text{(E)}$$

Eliminating S''' from equations (C) and (D), the value of R' is found to be

$$R' = r'R''/s' \qquad \text{(F)}$$

In a similar manner from equations (D) and (E) it is found that

$$R''' = r'''R''/s''' \qquad \text{(G)}$$

Note that the results in equations (F) and (G) are identical with those obtained previously.

To find the value of R'' substitute in equation (E) the values of R' and R''' from equations (F) and (G). When the resulting equation is reduced to its simplest form it is

$$vM\text{log}_e Rsr''R''S''^2 + vMr''^2S''^3 - Cs's''' = 0 \qquad \text{(H)}$$

The solution of equation (H) is demonstrated in Table 9, using the data of Doctor Garner's experimental results with tobacco. The reader should now be able to follow the computations according to the indicated directions in the explanatory column of the table.

TABLE 9.—*Computation of the optimum acreage to which to apply fertilizer costing a fixed amount*

[$100 to be spent for fertilizer. v=$0.14. Data are those of the tobacco experimental results]

	Step in computation	First trial	Second trial	Third trial	Fourth trial	Fifth trial	Sixth trial [1]
1	b, in units	10.0	11.0	11.1	11.2	11.3	11.24
2	$p+b$, in units	12.43	13.43	13.53	13.63	13.73	13.67
3	$1-R^{p+b}$	.93757	.95005	.95116	.95223	.95329	.95266
4	R^{p+b}	.06243	.04995	.04884	.04777	.04671	.04734
5	$r'R^{p+b}$	.067924	.054346	.053138	.051974	.050820	.051506
6	$r''(1-R^{p+b})$	.368465	.373370	.373806	.374226	.374643	.374395
7	Add steps 5 and 6	.436389	.427716	.426944	.426200	.425463	.425901
8	Divide step 5 by step 7, giving R^{n+a}	.155650	.127061	.124461	.121947	.119446	.120934
9	$1-R^{n+a}$	.844350	.872939	.875539	.878053	.880554	.879066
10	$n+a$, in units	8.34	9.25	9.34	9.43	9.53	9.47
11	a, in units	3.36	4.27	4.36	4.45	4.55	4.49
12	a' $(=a+q')$, in units	3.36	4.27	4.36	4.45	4.55	4.49
13	$r'''R^{p+b}$	.024036	.019235	.018803	.018391	.017983	.018226
14	Add steps 6 and 13	.392501	.392605	.392609	.392617	.392626	.392621
15	Divide step 13 by step 14, giving R^{k+c}	.061238	.048993	.047892	.046842	.045802	.046421
16	$1-R^{k+c}$	.938762	.951007	.952108	.953158	.954198	.953579
17	$k+c$, in units	12.52	13.52	13.62	13.72	13.82	13.76
18	c, in units	8.44	9.44	9.54	9.64	9.74	9.68
19	c' $(=c+q''')$, in units	8.44	9.44	9.54	9.64	9.74	9.68
20	b' $(=b+q'')$, in units	10.00	11.00	11.10	11.20	11.30	11.24
21	$r'a'$	3.66	4.645760	4.744	4.841600	4.950400	4.885120
22	$r''b'$	3.93	4.323	4.362	4.401600	4.440900	4.417320
23	$r'''c'$	3.25	3.634	3.673	3.711400	3.749900	3.726800
24	Add steps 21, 22, and 23	10.84	12.60	12.78	12.954600	13.141200	13.029240
25	Multiply step 24 by $(vM \log_e R)$	−479.021	−556.795	−564.749	−572.46505	−580.710929	−595.763405
26	r'' (step 4) (step 3)^2	.021567	.017718	.017365	.017023	.016682	.016885
27	Multiply step 25 by step 26	−10.331046	−9.865294	−9.806866	−9.745073	−9.687420	−9.721765
28	(Step 3)^2 vMr''^2	25.207748	26.227821	26.320	26.409022	26.497543	26.444696
29	(Step 7) (step 14) $(-C)$	−17.1283	−16.792344	−16.762206	−16.733337	−16.704784	−16.721768
30	Add step 27 and step 29	−27.459346	−26.657638	−26.533	−26.478410	−26.392204	−26.443533
31	Add step 28 and step 30	−2.251598	−.430	−.213	−.069388	.105339	.001160

[1] The number of units of b (=11.24) is approximated by graphing the values of step 31 at 11.2 and 11.3. When the correct value of b is reached, step 31 is zero. Running the computation shows that 11.24 is close enough.

Optimum average $=q=K+\text{step } 24=\frac{100}{13.02924}=7.625$.

Using a 10 per cent P_2O_5 fertilizer, 613 pounds will be needed (=11.24 units of 5.452 pounds).

Associated ammonia $=a'=a+q'$,=4.49 units of 6.203 pounds=27.85 pounds which is 4.55 per cent of 613 pounds.

Associated potash$=c'=c+q'''$=9.68 units of 5.064 pounds=49.02 pounds, or 8 per cent of 613 pounds.

The problem has been worked out for a case in which the fixed amount spent for fertilizer is $100, and on the assumption that there is no plant-food absorption; that is, that all three values of q are zero. Other than v, taken as $0.14, and $M=1{,}414.53$, the values of the quantities are those previously reached. The answer in this case is: 613 pounds per acre of a 4.5–10–8 fertilizer applied to 7.675 acres will give the maximum profit when only $100 is to be spent for fertilizer.

Note that several trials more than those shown in Table 9 may be needed, but the trials may best begin with a value of b about that giving the best results in the previous work. Whole units may be used in establishing the approximate value of b, then tenths. The second decimal place may be determined by graphing. Two decimal places in the value of b will give suffiicently close results.

CASE 2. Maximum profit per dollar's worth of fertilizer.

The equation expressing the profit on the entire amount of fertilizer is

$$P = gv(y - y_0) - K \qquad \text{(A)}$$

in which the values of g and of y are those used in case 1. When these values are substituted in equation (A) and the resulting equation is differentiated with respect to a, to b, and to c, the derivatives placed equal to zero give values of R' and of R''' the same as found in case 1. When these values are substituted in the equation formed by placing the derivative with respect to c equal to zero, the equation reduced to its simplest form becomes

$$M \log_e Rsr'' R'' S''^2 + Mr'' S''^3 - y_o s' s''' = 0$$

The solution of this equation for the tobacco experimental results is given in Table 10.

TABLE 10.—*Computation of the application that will yield the maximum profit per dollar's worth of fertilizer*

[Data are those of the tobacco experimental results. In addition to the evaluations reached in case 1 the following are needed: $M \log_e R = -315.644$; $Mr''^2 = 218.472744$; and $y_0 = 237.373$]

	Step in computation	No plant food absorption. ($q=0$)					1.32 units of P_2O_5 absorbed. ($q''=1.32$)		
		First trial	Second trial	Third trial	Fourth trial	Fifth trial[1]	First trial	Second trial	Third trial[1]
1	b, in units[1]	10.	5.	4.	3.9	3.87	3.87	4.4	4.47
2	$p+b$, in units	12.43	7.43	6.43	6.33	6.30	6.30	6.83	6.90
3	$1-R''$	.93757	.80947	.76184	.75647	.75483	.75483	.78218	.78556
4	R''	.06243	.19053	.23816	.24353	.24517	.24517	.21782	.21444
5	$(1-R'')^2$	.879038	.655242	.580400	.572247	.569775	.569775	.611806	.617105
6	$(1-R'')^3$	.824159	.530398	.442172	.432888	.430083	.430083	.478542	.484773
7	$r'\ R''$	.067924	.207297	.259118	.264961	.266745	.266745	.236988	.233311
8	$r''\ (1-R'')$	.368465	.318122	.299403	.297293	.296648	.296648	.307397	.308725
9	(Step 7)+(Step 8)	.436389	.525419	.558521	.562254	.563393	.563393	.544385	.542036
10	(Step 7)÷(Step 9)$=R'$	.155650	.394537	.463936	.471248	.473462	.473462	.435332	.430435
11	$1-R'$	.844350	.605463	.536064	.528752	.526538	.526538	.564668	.569565
12	$n+a$, in units	8.34	4.17				3.35	3.73	3.78
13	a, in units	3.36	−.81						
14	a', $(=a+q')$	3.36	−.81						
15	$r''\ R''$	.024036	.073354	.091692	.093759	.094390	.094390	.083861	.082559
16	(Step 15)+(step 8)	.392501	.391476	.391095	.391052	.391038	.391038	.391258	.391284
17	(Step 15)÷(step 16)$=R'''$	.061238	.187378	.234449	.239761	.241383	.241383	.214337	.210995
18	$1-R'''$	.938762	.812622	.765551	.760239	.758617	.758617	.785663	.789005
19	$k+c$, in units	12.52	7.505	6.50	6.40	6.37	6.37	6.90	6.97
20	c, in units	8.44	3.425	2.42	2.32	2.28	2.28	2.82	2.89
21	c', $(=c+q''')$	8.44	3.425	2.42	2.32	2.28	2.28	2.82	2.89
22	b', $(=b+q'')$	10.0	5.0	4.0	3.9	3.87	5.19	5.72	5.79
23	$r'\ a'$	3.66							
24	$r''\ b'$	3.93	1.965	1.572	1.5327	1.521	2.040	2.247960	2.275470
25	$r'''\ c'$	3.25	1.319	.932	.8932	.878	.878	1.085700	1.112650
26	(Step 23)+(step 24)+(step 25)	10.84	3.284	2.504	2.4259	2.399	2.918	3.333660	3.388120
27	(Step 26) $M \log_e R$	−3421.581	−1036.575	−790.278	−765.721	−757.138	−921.049192	−1052.249777	−1069.439749
28	(Step 5) $r''\ R''$	.021567	.049063	.054324	.054768	.054899	.054899	.052373	.052006
29	(Step 27) (step 28)	−73.793	−50.857	−42.931	−41.937	−41.566	−50.564680	−55.109478	−55.617284
30	(Step 6) Mr''^2	180.056	115.878	96.603	94.574	93.961	93.961	104.548348	105.909688
31	(Step 9) (step 16) $(-y_0)$	−40.658	−48.825	−51.851	−52.191	−52.295	−52.295	−50.559259	−50.344443
32	(Step 29)+(step 31)	−114.451	−99.682	−94.782	−94.128	−93.861	−102.859680	−105.668737	−105.961727
33	(Step 30)+(step 32)	65.605	16.196	1.890	.446	.100	−8.898680	−1.120353	−.052039

[1] When the correct value of b is reached, step 33 is zero. The values of b, =3.87, and =4.47 were approximations reached by graphing and prove to be close enough. The computations are carried out in full, as steps 14, 21, and 22 show the quantities of plant foods to be used in making up the fertilizer and steps 23, 24, and 25 show the cost per acre.

When plant-food absorption is not involved, the application that will give most profit per dollar's worth of fertilizer is one made up with 3.87 units, or 21.1 pounds, of phosphoric acid, and 2.28 units, or 11.55 pounds, of potash, worth together $2.40 per acre. No nitrogen is to be used in this fertilizer. Using 10 per cent of phosphoric acid, the analysis works out as 0–10–5.5, worth $22.75 per ton.

One might fertilize 41.67 acres with $100 worth of fertilizer at this rate. This does not mean that it would be profitable to spread the fertilizer so thinly; there might, in fact, be a heavy loss on the entire acreage. Still the increase in yield attributable to the fertilizer would be greater from such an application than that from any other.

When plant food is absorbed the computations are the same except for the values of some of the items. The three columns on the right side of Table 10 illustrate the work when it is known that phosphoric acid is absorbed by the soil, assuming a rate amounting to 1.32 units. The application which gave most profit per dollar's worth of fertilizer when there was no absorption proves to be too small (first trial). The second trial shows that 4.4 units is also too small, but the two trials provide means of approximating the figure to use in the third trial—graphing on a large scale indicates a value slightly larger than 4.47 units of b, (actually 4.4736), but computation proves that 4.47 is close enough. The results in this case call for an application of about 316 pounds of 0–10–4.65 fertilizer on 29.5 acres. The $100 available would buy 4.656 tons of this fertilizer, and the cost would be $21.48 per ton.

Case 3. Fixed acreage, H; fixed expenditure for fertilizer, K; optimum acreage, g, to which to apply the fertilizer.

In this case the profit from the H acres is

$$\begin{aligned} P &= gvy + (H-g)vy_0 - HC - K \\ &= gv(y-y_0) + Hvy - HC - K \end{aligned} \qquad \text{(A)}$$

Note that the variable term of equation (A) is identical with the variable term of the corresponding equation in case 2. This means that the three derivatives of the equation are identical with those of the preceding case. The solution of the problem is also identical, so that this case is in reality merely a matter of finding the fertilizer formula, the application per acre, and the number of acres required to yield the greatest profit per dollar invested in fertilizer.

But in this case the actual acres planted may be larger than the number required to give maximum profit per dollar's worth of fertilizer, so that the profit or loss from the entire crop may not be the same as in case 2.

In general the solution of the problem of greatest profit per dollar invested in fertilizer is of limited importance. The more important problem in cases where the value of fertilizer available is fixed is to find the optimum acreage to grow (and fertilize) in order to obtain maximum profit from the entire crop.

ABSORPTION, OR OCCLUSION, OF PLANT FOOD

As stated in the introduction, on some soils applications of a growth factor up to a certain (usually small) quantity appear to have no effect on yields. A number of such cases are cited below. For some reason not yet definitely understood, these small applications are not available to the growing crop. Soil chemists who have

recognized the phenomenon refer to it as "absorption." In the absence of a better term based on more complete understanding, it will here be referred to as plant-food absorption by the soil. As suggested in the introduction, perhaps a better term would be plant-food occlusion by the soil.

When the amount of the growth factor applied exceeds the quantity thus held unavailable in the soil, the yield begins to increase, and appears to follow quite accurately the exponential yield curve.

According to O. W. Willcox, in a letter to the author, there are soils in Hawaii which absorb some 60 per cent of all the potash applied to them, irrespective of the quantity applied. Such cases would require different treatment from that outlined below, but may be brought within the scope of the yield curve when more knowledge is available of the "effect factors" discussed by Willcox (*11*).

When plant-food absorption of the first type above described occurs, the yield of a plot receiving none of the variable growth factor, that is, the yield of an unfertilized check plot, does not lie on the yield curve; it therefore can not be properly used in determining the constants of the yield equation. That this difficulty may be obviated by disregarding the yield on plots receiving none of the variable factor is shown by the data presented below.

Figure 9 shows the yields of corn on four plots fertilized with different quantities of phosphoric acid and a check plot receiving no phosphoric acid at the Snowshoe branch of the Pennsylvania State station (*9*). In this figure it is seen that the yield on the plot receiving no phosphoric acid is not in line with the remaining yields. The constants in the yield equation in this case were calculated from the yields of plots receiving, respectively, 1, 2, 3, and 4 units of phosphoric acid, a unit being 24 pounds.

The yield curve appears to offer a means of calculating the amount of the plant-food element absorbed by the soil. The method of finding this amount is to find the abscissa of the curve at the point at which the yield as indicated by the curve is equal to the yield without fertilizer. In Figure 9 this point is seen to lie at 0.3 unit, or 7.2 pounds of phosphoric acid, to the right of the origin.

If this interpretation is correct, then the yield should have been the same for any quantity of phosphoric acid from 0 up to 7.2 pounds per acre.

The corn for which the curve of Figure 9 was constructed was grown in rotation with oats, wheat, and hay. The oats and wheat exhibit the same absorption phenomenon, the amount of absorption for oats being approximately the same as for corn, while for wheat it was considerably larger (*6*). This is consistent with the known fact that corn can extract from the soil considerably larger quantities of phosphoric acid than can wheat.

On the hay plot receiving no phosphoric acid there was a large growth of weeds, which vitiated the yield for that plot, so that it can not be included here.

The constants in the yield curve for the corn, oats, and wheat in this Pennsylvania experiment were first calculated from the yields of all five of the plots, including the check plot which received no phosphoric acid. They were then recalculated omitting the yield on the check plot. A comparison of the departures of the curve from the observed yields for the two cases is shown in Table 11.

TABLE 11.—*Improvement in fit of yield curve when phosphoric acid absorption is taken into account*

x	Errors in calculated yields of—					
	Corn		Oats		Wheat	
	Y_0 in	Y_0 out	Y_0 in	Y_0 out	Y_0 in	Y_0 out
0	−0.28		−0.13		−0.13	
1	.67	−0.12	.45	−0.07	.44	−0.01
2	.02	.47	−.30	.28	−.30	.10
3	−1.02	−.64	−.35	−.38	−.36	−.19
4	.60	.28	.34	.17	.34	.11
Average of squares	.38	.18	.11	.06	.11	.01

The first column for each crop shows the residuals when the yield on the check plot is included, the second, when the check plot is

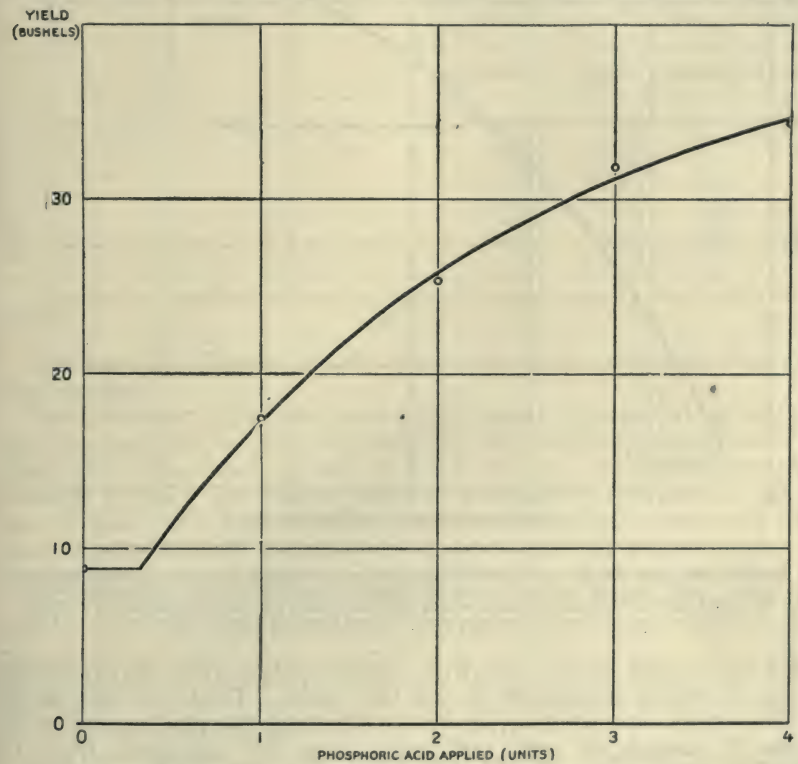


FIGURE 9.—MEASURING ABSORPTION OF PHOSPHORIC ACID

The observed yields (bushels of corn per acre) on the plots receiving phosphoric acid lie close to the exponential yield curve. The yield on the check plot, which received no phosphoric acid, 8.8 bushels does not lie on the curve. The amount of absorption is shown by the abscissa of the break in the curve, which occurs at the point $x=0.3$, in this case 7.2 pounds of phosphoric acid per acre. (The data were obtained from Bulletin 166 of the Pennsylvania Agricultural Experiment Station (*9*).)

omitted. In the case of corn, omitting the check plot more than doubled the accuracy of the fit, the measure in the one case being 0.38 and in the other 0.18; that is, the fit of the curve in the second

column is more than twice as good as in the first. A nearly similar increase in closeness of fit is seen in the case of oats. In the case of wheat, improvement in fit by omitting the check plot is still more marked. These results are consistent with the fact that the amount of absorption, when measured by the method of Figure 9, in the case of oats is slightly less, in the case of wheat markedly greater, than in the case of corn. The check-plot yield in the oats series is therefore slightly less distant, that in the wheat series considerably more distant, from the yield curve than that in the corn series.

Part of the improvement in fit observed in these cases may be due to the fact that the yield curve can be made to fit four observations

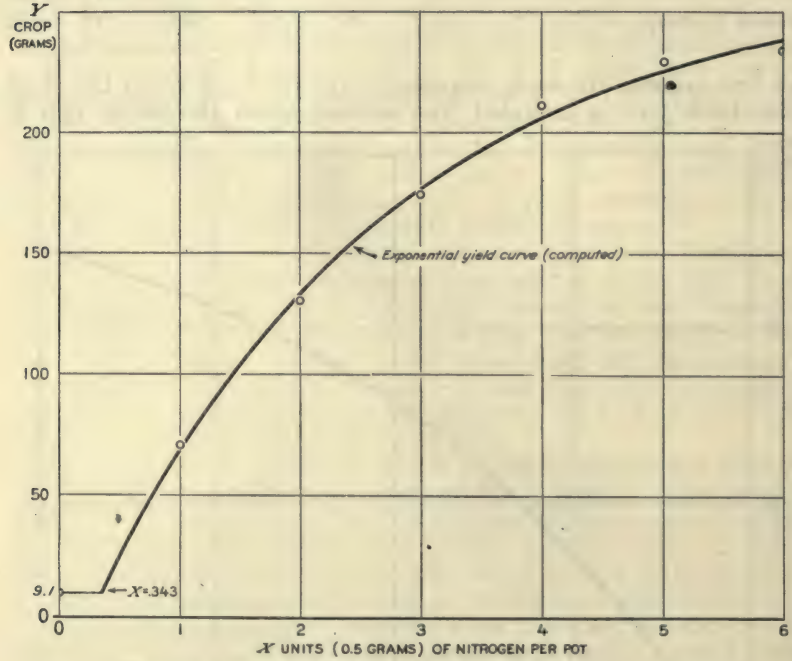


FIGURE 10.—MEASURING THE ABSORPTION OF NITROGEN

In this series, also, the observed yields lie close to the exponential yield curve computed from them. Again, the pot receiving no nitrogen produced 9.1 grams of crop, which would lie on the yield curve at the point where $x=0.343$ unit of nitrogen per pot, the measure of nitrogen absorption of the soils used in the experiment. Data from Niklas and Miller (*3*).

more accurately than it can five, assuming the errors of experiment to be of similar magnitude in the two cases. That it is not all due to this cause can easily be shown by omitting the plot receiving four units of phosphoric acid and calculating the constants from the remaining four (including the check plot). When this is done, it will be found that the fit is even poorer than when the five plots are included.

Figure 10 shows a similar situation in the case of nitrogen. Niklas and Miller (*3*) have assembled nine series of experiments in which nitrogen was the variable fertilizer element, each of which clearly exhibits the phenomenon of nitrogen absorption. Figure 10 is a graphic presentation of one of these nine series. The constants in the yield equation were calculated first with the check plot receiving

no nitrogen included, and second with this plot omitted. Both the exponential curve of Mitscherlich and the parabolic curve advocated by Niklas and Miller were applied to each of the nine series.

Table 12 gives a comparison of the average squared residuals for both curves, with and without the check plot. In the case of the parabolic curve the fit is improved in six of the nine cases by omitting the unfertilized plot. In the case of the exponential curve the fit is improved in each of the nine cases. This indicates strongly that the check plot does not belong in the series. Figure 10 indicates that 0.343 unit of nitrogen, each unit being 0.5 gram, was absorbed, and had no effect on the yield.

TABLE 12.—*Improvement in fit of curves when nitrogen absorption is taken in account*

Series [1]	Average squared residuals from the—			
	Parabolic curve		Exponential curve	
	y_0 included	y_0 omitted	y_0 included	y_0 omitted
4	13.93	8.20	17.78	13.66
5	8.52	1.06	33.61	13.25
6	26.69	14.22	24.74	5.77
7	12.78	5.46	13.51	6.09
8	5.47	5.13	5.29	3.20
9	10.87	12.73	8.67	3.00
10	3.88	4.02	6.20	2.17
11	13.50	8.45	15.97	7.18
12	.80	1.48	5.82	2.18

[1] Nine experiments assembled by Niklas and Miller (*3*), in which nitrogen was the variable fertilizer element.

The data for Figure 10 and Table 12 were obtained from pot experiments.

The presence of this absorption phenomenon is indicated by the large positive residuals for the plot receiving one unit of fertilizer when the check plot is included, as seen in Table 11. In the case of corn, this residual is 0.67, the largest positive residual in the series. In the case of oats, it is 0.45, and in the case of wheat, 0.44, in each case being the largest positive residual in the series. Similar remarks are applicable to the nitrogen series dealt with by Niklas and Miller (*3*).

It is readily seen that the yields of check plots receiving no fertilizer should not be used in calculating the constants of the yield equation in cases where plant-food absorption by the soil occurs. In conducting fertilizer experiments on such soils the standard check plots should receive at least as much of each growth factor as the soil is capable of rendering unavailable.

But plots receiving no fertilizer have certain economic importance, as pointed out in the introduction. The knowledge they give is of value in cases in which it seems necessary to spread a limited quantity of fertilizer over a large acreage. Where it is feasible to do so, therefore, plots receiving no fertilizer may be included along with the standard check plots receiving fixed amounts of each factor (p. 58).

FORM OF THE YIELD CURVE

Amongst European soil scientists there has been much discussion of the form of the yield curve. Mitscherlich and those who support his contentions claim that an exponential curve represents the relation between yield and amount of a growth factor made available to the growing plant. A considerable number of other scientists, including Niklas and Miller, (*3*) contend that a parabolic curve is the true yield curve. In the article referred to, Niklas and Miller bring together 12 series of experiments by various soil scientists, and make a comparison of the fit of the two curves in each of the 12 series. They had not recognized the presence of the phenomenon of nitrogen absorption which appears to be present in nine of their series, so in their calculations they included the yield of plots receiving no fertilizer. They determined the constants of the parabolic equation for each series by the method of least squares, and calculated the resulting residuals. They compared these residuals with those arrived at by Mitscherlich, who used some method of approximation, and not the method of least squares, in arriving at the constants in his equation. In general, the fit of the parabolic curve was better than that of the exponential curve when the comparison was made on this basis.

The present writer has recalculated by the method of least squares, the constants of both curves for each of the 12 series, omitting the check plot in the case of the nitrogen series, and finds that in 6 of the 12 cases the exponential curve, and in the remaining 6 the parabolic curve, gives the best fit. These results therefore offer no basis for determining which of the curves comes nearest to expressing the true relation between yield and fertilizer applied.

The exponential equation, however, contains only two constants, whereas the parabolic equation contains three constants. It is well known that the larger the number of constants in an equation the wider the range of observations it can be made to fit. If the number of constants equals the number of observations, the fit can be made exact. The fact, therefore, that a 2-constant curve fits the observed results in 12 series (of 4 to 8 observations each) as well as a 3-constant curve is an indication that the 2-constant curve may more nearly express the existing relation than does the 3-constant curve.

A comparison of much greater significance is made in Tables 13 and 14. The assumption appears to be justified that a curve which really expresses the relation between yield and fertilizer application should give accurate results when it is used to extrapolate yields beyond the range of yields used in determining the constants in the equation, provided the yields used are accurate. A comparison of extrapolation with the two curves is given in Table 13 for the phosphoric acid series, and in Table 14 for seven of the nitrogen series used by Niklas and Miller in their article (*3*). The two remaining nitrogen series were short, with their terms equally spaced, and did not lend themselves well to a comparison of this kind.

In the case of the phosphoric acid series (Table 13) there was no indication of phosphoric acid absorption. It also happened that the last plot received four times as much fertilizer as the preceding plot. The constants in each equation were therefore calculated from the yields on the first three plots, the residuals in each case all being zero. The equations thus obtained were then used for extrapolating the yield of the fourth plot. The actual yield of the fourth plot in the

first series was 50.6. The yield calculated by the exponential curve was 51.7, the residual, that is, the difference between the observed and the calculated yield, being 1.1. This must be considered highly accurate extrapolation. In the case of the parabolic curve the calculated yield of the fourth plot was 5.0, the residual being −45.6, a very poor result. In the case of series 2 neither curve gave very good results, presumably because of inaccuracy in the yields of one or more of the three preceding plots. It will be observed, however, that while the observed yield was 52.5 on the fourth plot, the yield calculated by the parabolic curve was −129.8, a result extraordinarily poor.

In the case of series 3 the comparison gives little advantage to either curve, both results being poor.

It is obvious that a comparison of this kind, to be decisive, must be based on yields ascertained with a very high degree of accuracy. A small experimental error in the case of any one plot, where the constants are calculated from only three plots, makes a marked difference in the results of extrapolation. Though the result of this comparison is distinctly more favorable to the exponential curve than to the parabolic, the data on which the comparison is based are too limited to be definitely conclusive.

In Table 14 the comparison is more nearly conclusive. It shows the residuals for seven experimental series in which nitrogen was the variable growth factor. In each series the constants of both yield equations were calculated (by the method of least squares) from the yields of the first five plots, and the yields of the remaining three plots were then calculated by the equation thus obtained.

TABLE 13.—*Results of extrapolation by means of the parabolic curve (P) and the exponential curve (E), the constants of each being computed from three observations*

[Curves fitted to $x=0$, $x=0.10$, and $x=0.25$; errors at these points are 0.]

Series [1]	Yield at $x=1.00$			Errors, using—	
	Actual	Extrapolated, using—			
		P	E	P	E
1	50.6	5.0	51.7	−45.6	1.1
2	52.5	−129.8	38.2	−182.3	−14.3
3	44.9	87.2	92.3	42.3	47.4

[1] Phosphoric acid series of Niklas and Miller (5).

It will be observed that in series 7, 9, 10, and 11, the fit of the parabolic curve within the range used in determining the constants is better than that of the exponential curve. This may be interpreted as resulting from the larger number of constants in the parabolic curve. Yet in these series the extrapolation by the exponential curve is very much better in three and considerably better in the fourth than by the parabolic curve. In series 6 the exponential curve gives a better fit in the case of the first five plots than the parabolic, and the fit of the extrapolated yields is more than eight times as accurate with this curve as with the parabolic. In series 8

the fit of the two curves to the first five yields is approximately the same, but the extrapolation is slightly in favor of the exponential curve. In series 12 the fit of the exponential curve is better than that of the parabolic although the fit of the extrapolated yields is not so good.

Of the entire seven series the results with the exponential curve are best in six, and with the parabolic curve in one. Here, again, it must be noted that great accuracy in the experimental yields is necessary in a comparison of this kind.

TABLE 14.—*Fit of the parabolic curve (P) compared with that of the exponential curve (E) in seven series,*[1] *within the range of the first five observations used in computing the constants of the curves, and extrapolations*

Observation point	Series 6		Series 7		Series 8		Series 9		Series 10		Series 11		Series 12	
	P	E	P	E	P	E	P	E	P	E	P	E	P	E
ERRORS WITHIN THE RANGE USED IN COMPUTING THE CONSTANTS														
$x=0.25$	2.11	1.07	0.04	−0.47	0.08	−0.03	0.09	−0.25	−0.28	−0.56	−1.00	−1.03	0.27	0.01
$x=0.50$	−4.39	−3.02	.23	.68	.21	.28	−.47	.47	1.19	1.95	2.32	3.00	−.28	.21
$x=0.75$	.88	1.26	−.94	1.35	−1.04	−.86	.85	.58	−1.88	−2.09	−.96	−1.50	−.84	−.80
$x=1.00$	3.33	2.45	1.03	−2.96	1.01	1.07	−.67	−1.71	1.31	.47	−1.04	−2.11	1.36	.94
$x=1.25$	−1.75	−1.79	−.36	1.39	−.32	−.45	.19	.89	−.34	.22	.68	1.66	−.55	−.37
Average of squares	7.33	4.26	.43	2.64	.45	.43	.29	.87	1.37	1.75	1.77	3.90	.60	.34
ERRORS OF THE EXTRAPOLATED YIELDS														
$x=1.50$	−9.36	−4.74	4.60	−7.95	4.73	4.29	−2.58	3.85	−9.24	−3.96	3.20	10.10	−.05	2.58
$x=1.75$	−23.40	−9.02	14.20	−11.58	14.46	13.59	−16.38	.88	−15.48	−1.25	−9.18	8.81	−.93	6.62
$x=2.00$	−45.57	−15.39	22.84	−8.32	23.26	21.84	−36.31	−2.38	−29.56	−1.47	−25.66	9.05	−4.30	11.16
Average of squares	903.93	113.56	248.15	88.83	257.40	226.69	531.12	7.09	399.60	6.47	165.45	87.17	6.45	58.34

[1] Of the nitrogen series of Niklas and Miller (*3*) as recomputed.

In Tables 15 and 16, relating to series 10 of the Niklas and Miller paper, the comparison is made in a different manner. Table 15 gives the residuals for all values of x obtained from each curve when values of x from 1 to 8 were used in determining the constants in both equations.

TABLE 15.—*Residuals in series 10 when Y_1 to Y_8 are used in calculating the constants in the parabolic curve (P) and the exponential curve (E)*

Value of x	Residuals		Value of x	Residuals	
	P	E		P	E
1	1.61	−.59	5	2.50	1.16
2	−.15	1.85	6	−.36	−2.60
3	−4.14	−1.95	7	1.75	.52
4	.44	.98	8	−1.66	.66

TABLE 16.—*Relative fit and correctness of extrapolations of the parabolic curve (P) and the exponential curve (E) when the values of Y used in calculating the constants are as shown in first column*

[Data of series 10]

Values of Y used in calculating the constants	Average of squared residuals—			
	Within range of Y values used		For extrapolated values of Y	
	P	E	P	E
Y_1 to Y_4	1.46	0.51	668.33	2.25
Y_1 to Y_5	1.38	1.75	399.60	6.47
Y_1 to Y_6	3.69	2.23	31.58	13.96
Y_1 to Y_7	4.76	4.10	99.40	.50

In Table 16 the average of the squared residuals is given for each curve when the constants are calculated (1) from yields Y_1 to Y_4, (2) from yields Y_1 to Y_5, (3) from yields Y_1 to Y_6, and (4) from yields Y_1 to Y_7. With the constants thus determined, the yields are then calculated (1) within the range of the Y values used in calculating the constants, and (2) beyond this range.

Within the range of Y values used in calculating the constants, both curves give fair agreement with observed yields, the exponential curve giving the best fit in three cases, the parabolic curve in one.

When the two curves are used in calculating the extrapolated yields, the exponential curve gives fair results in all cases, but the parabolic curve falls down badly.

It will be observed that the case in which the parabolic curve gives moderately good results is the one in which the last yield used in calculating the constants is very high. This condition tends to bend the curve upward, and thus to increase its radius of curvature.

The question which of these curves more nearly expresses the relation between yield and fertilizer application must be settled on the basis of comparisons similar to those above.

Note that in series 12 the fifth residual is negative in the case of both curves, also the third residual, whereas the fourth residual is positive. This distribution of experimental errors tends to increase

the radius of curvature of both curves. A little study of the two curves will show that this effect in the case of the parabolic curve is greater than in the case of the exponential curve. In general, the parabolic curve appears to give good extrapolations only in cases in which the experimental errors are such as to increase considerably its radius of curvature.

Though a decision of the question between these two curves can not be made definitely on the basis of the preceding results, the fact remains that the data at hand are strongly in favor of the exponential curve and against the parabolic curve. Because of the greater number of constants in the parabolic curve, it can be made to fit a wider range of experimental results than can the exponential curve, but the real test comes when the two curves are used for extrapolation. In the comparisons it has been possible to make here the evidence is strongly in favor of the exponential curve.

It will probably be conceded that the exponential curve gives at least as good a fit to experimental data as the parabolic curve within the range of the yields used in computing the constants of the two curves.

Assuming, then, that within the usual range of fertilizer applications in practical farming the exponential curve gives as good results as the parabolic, there is another important reason for preferring the exponential curve. It is the fact that the exponential equation may be so written as to apply to cases in which two or more growth factors vary. At present, at least, this is not the case with the parabolic curve.

Some of the advantages of this more general type of equation are:

(1) When the constants have been evaluated, the equation may be used in calculating the yield from any quantity of fertilizer of any composition, within the toxic limit of the fertilizer.

(2) It may be used in determining the most profitable amounts of nitrogen and potash to use with any desired quantity of phosphoric acid.

(3) It may be used in determining the most profitable quantity of fertilizer having the optimum analysis to use in any case.

For these reasons, it would appear to be justifiable to use the exponential curve until something better presents itself.

DERIVATION OF THE EXPONENTIAL YIELD CURVE

ONE-VARIABLE FORM

The exponential yield curve for a single variable growth factor is illustrated in Figure 1.

In the figure, horizontal distances along the X axis represent amounts of a causal factor, vertical distances the amount of the resulting effect. Thus, if 50 pounds of potash per acre be taken as a unit of the causal factor, then the figure shows the effect of four such units on yield of a crop. The first unit produces an increase in yield represented by a; the second unit produces a further increase, b; the third unit produces increase c, and so on.

An important property of the curve of Figure 1 is that the quantities a, b, c, d, etc., are the terms of a decreasing geometric series, having a constant ratio. Thus, if b is 60 per cent of a, then c tends to be 60 per cent of b; d, 60 per cent of c; and so on. When the quantity of the growth factor becomes large enough to become injurious to the crop, the curve no longer applies.

In the figure, the ratio of the series is 0.6, each term of the series (after the first term) being 0.6 of the preceding term.

The curve of Figure 1 is seen to approach a horizontal line at distance A above the X axis. A is thus the limit toward which the value of the ordinate of the curve approaches as the quantity of the growth factor, potash, increases.

Observe that in Figure 1, if we let y_1, y_2, y_3, etc., represent, respectively, the increase in yield due to 1, 2, 3, etc.. units of the growth factor then

$$\begin{aligned} y_1 &= a \\ y_2 &= a+b \\ y_3 &= a+b+c \\ y_4 &= a+b+c+d \\ y_x &= a+b+c+\ldots+x \end{aligned}$$

If, now, R represent the ratio of the decreasing geometric series, a, b, c, d, etc., then

$$\begin{aligned} b &= aR \\ c &= bR = aR^2 \\ d &= cR = aR^3 \end{aligned}$$

The equation for y_x may therefore be written:

$$y_x = a+aR+aR^2+aR^3+\ldots+aR^{x-1}$$

Multiplying through by R,

$$Ry_x = aR+aR^2+aR^3+\ldots+aR^{x-1}+aR^x$$

Subtracting this last from the preceding equation,

$$y_x(1-R) = a-aR^x = a(1-R^x)$$

whence

$$y_x = \frac{a}{1-R}(1-R^x),$$

which shows the increase in yield for x units of the growth factor.

Since R is less than 1, as x increases, R^x decreases; and as x approaches infinity, R^x approaches zero. Hence, if A represent the value of y_x when x is infinite, we have

$$A = \frac{a}{1-R}$$

Substituting A for $\frac{a}{1-R}$, and dropping the x subscript, the yield equation may be written

$$y = A(1-R^x) \qquad (13)$$

This equation expresses the relation between increase in yield and increase in a growth factor when all other growth factors are held constant.

The writer discovered this equation in 1920 (*4*) and later learned that it had also been discovered in 1912 by the German experimenter Mitscherlich (*2*). Mitscherlich has shown that the formula has wide applicability to the soils of eastern Germany, while the present writer has shown its applicability to many soils in the United States, especially in eastern humid regions, as far west as Indiana and Michigan (*7*).

In the writer's earlier work, equation (13), or rather, a modified form of it seen in the equation $Y = M - AR^x$, the derivation of which

is given later, was applied to experiments in which the unit of x was a given quantity of a mixed fertilizer, so that all three constituents varied together (in the same ratio). That this procedure is ordinarily justified is seen in the curve of Figure 11, in which the yield for different quantities of fertilizer is shown, the unit being 100 pounds of 10–10–10 fertilizer.

This curve shows results such as should be obtained in water or sand cultures, in which the total quantity of each plant-food element available to the plant is known.

The curve is at first (i. e., for small values of x) convex downward; for higher values of x it is concave. It therefore has a point of inflection.

In ordinary fertilizer practice, especially on fairly good soils, the lower part of this curve represents growth due to plant food in the soil. Where the supply of such material in the soil is equivalent to

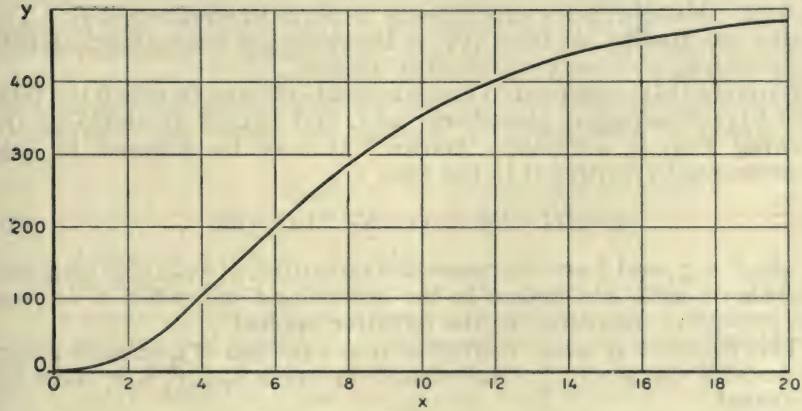


FIGURE 11.—YIELD CURVE FOR THREE VARIABLE GROWTH FACTORS

Abscissas represent units of fertilizer, a unit being 100 pounds of 10–10–10 fertilizer. Ordinates represent yields. The curve is a so-called S curve.

four of the units of fertilizer applied, then the part of the curve obtained by experiment would be that part to the right of the vertical line at $x=4$. This part is seen to have about the same form as the curve of Figure 1, which applies to a single plant-food element, and the experimental results with the mixed fertilizer could be fitted to observations based on equation (1) very satisfactorily. In any case in practice, it is the upper part of the curve that is important, and this part always has a form similar to that of Figure 1.

The curve of Figure 1 represents increases in yields as the quantity of a growth factor made available to the crop increases. If Y_0 represent yield when the quantity applied is zero, and if this yield be added to each member of equation (13), then

$$y+Y_0=A+Y_0-AR^x \qquad (A)$$

Since Y_0 is the yield for $x=0$ and y the increase in yield for x units of the factor, then $y+Y_0$ is the actual yield, Y, for x units. Also, since A is the maximum increase in yield from $x=0$ to $x=\infty$, then $A+Y_0$ is the theoretical maximum obtainable yield, M, with any

quantity of the factor. Equation (A) above may therefore be written

$$Y = M - AR^x$$

which is equation (1) of the preceding discussions.

GENERAL FORM

The German mathematician Baule (*1*) was the first to point out that when two or more growth factors are varied at the same time, the exponential yield equation has the form

$$y = A(1 - R_1^{x_1})\ (1 - R_2^{x_2})\ (1 - R_3^{x_3}) \qquad (14)$$

in which x_1, x_2, x_3, etc., are the respective total quantities of the first, second, third, etc., growth factors available to the plant, while R_1, R_2, R_3, etc., are the ratios of the respective series of increments in yield due to successive equal increases in the respective growth factors. Mitscherlich's experiments conform to equation (14). The author has applied equation (14) to the results of some American field experiments, with very satisfactory results.

Formula (14) is adapted to water or sand cultures, in which the total quantity of nitrogen, phosphoric acid, and potash available to the growing crop is accurately known. It may be adapted to field experiments by writing it in the form

$$y = A(1 - R_1^{n+a})\ (1 - R_2^{p+b})\ (1 - R_3^{k+c}) \qquad (15)$$

in which n, p, and k are the respective quantities of available nitrogen, phosphoric acid, and potash in the unfertilized soil, while a, b, c are the respective quantities in the fertilizer applied.

This equation is easily converted into equation (7), already given, by suitable changes in the size of units in which n, a, p, b, k, and c are measured.

By means of a simple series of experimental plots, suitably arranged and fertilized, the constants A, n, p, and k, R_1, R_2, and R_3 can be determined for any crop on any soil which responds to fertilizers in accordance with equation (1) when a single plant-food element is varied. The yields of the plots will also reveal whether there is such response in any particular case.

Since equation (5) makes it possible to determine the available nitrogen, phosphoric acid, and potash in a given soil, it is capable of measuring the effect on available plant-food elements of such soil amendments as lime, manure, a green-manure crop, etc.; also the effect on available plant food of different methods of tillage. This may be done by running one series of experimental plots on land receiving lime, manure, a green-manure crop turned under, a given type of tillage, etc., and another similar series on similar land not receiving the treatment. Such series, if planned as suggested later herein, would give the values of n, p, and k for the soil on which each series is conducted. Comparison of these values for the two series would then show the effect of the treatment in rendering plant food available.

Again, plants do not use all the fertilizer elements applied to the soil, especially in the case of large applications. There may, therefore, be accumulations of fertilizer residues in heavily fertilized soils that become injurious to the succeeding crops. Such cases have occurred in practice, particularly amongst growers of truck crops in

certain localities. Equation (5) makes it possible to measure these residue accumulations by running a series of plots year after year, changing the plots to a new location each year. Each year the available nitrogen, phosphoric acid, and potash in the soil is measured. The rate of accumulation is thus made known, and the rate at which fertilizers are applied may be so adjusted as to take account of the changing quantities of plant food in the soil.

The above-mentioned advantages of a usable yield equation may be summarized as follows: When the constants of equation (7) have been determined then this equation and equation (5) may be used to determine—

(1) The yield from any quantity of the three ingredients.
(2) The most profitable fertilizer analysis.
(3) The most profitable quantity of this optimum analysis.

Equation (7) does not apply to the average results over a series of years on permanent or semipermanent experimental plots. The reason is that the more heavily fertilized plots change from year to year in content of available plant-food elements; hence the difference in yield between a lightly and a heavily fertilized plot, especially after the test has run several years, is due partly to difference in current applications and partly to unequal accumulations of plant-food elements in the soil.

(4) The effect of lime on the availability of plant food in the soil.
(5) The effect of a legume crop on the amount of available nitrogen in the soil.
(6) The change in amount of available plant food in the soil as a result of any system of tillage or of fertilizer application.

It is therefore essential to move the test plots frequently; that is, as soon as cumulative effects appear, to a new location. Replication of the plots will, of course, add to the reliability of the experimental results, and hence to the deductions to be made from them. The use of several different quantities of each growth factor is equivalent to replication of the fundamental series, and requires fewer plots, as will be pointed out later.

Fertilizers also affect the quality of certain crops, especially tobacco, of which effect the equation gives no hint; it deals with yields, not with quality of the product.

Many other conditions, such, for instance, as the length of day, the acidity of the soil, temperature, character of seed, all affect the yield of crops. Some of these may ultimately be brought in line with equation (7), but this is work for the future.

It may be remarked here that if other growth factors are found that conform to equation (1) above, they may be brought into the picture by adding a factor of the form $(1-R^x)$ to equation (7), and an additional series of plots in which the new factor is varied. Amount of irrigation water and intensity of sunlight have been shown to follow equation (1).

PLAN FOR OBTAINING DATA

Since the most general form of the yield equation contains seven constants, A, n, p, k, R_1, R_2 and R_3, the yields from at least seven plots, suitably fertilized, are necessary to determine the value of these constants. A larger number of plots, with suitable check plots, will add materially to the accuracy of the determinations.

SERIES OF PLOTS

In Table 17 of alternative series several series are outlined. The amount of nitrogen, phosphoric acid, or potash to use as a unit in each case is more or less an empirical matter. The units should be such that the largest application of each fertilizer constituent will produce 80 to 90 per cent of the total possible effect of that constituent. In any given case, unless something is already known of the crop response to fertilizers, it may be necessary to run a preliminary test the first year before deciding how many pounds per acre shall be taken as the unit of nitrogen, how many as the unit of phosphoric acid, and how many as the unit of potash. It is not at all essential that the unit of each constituent should be the same.

The number of units of each fertilizer constituent to use on the various plots in the series is also more or less an arbitrary matter. The numbers suggested in the table greatly simplify the mathematical work in computing the value of the constants.

TABLE 17.—*Alternative series of fertilizer plots*

[*a*=nitrogen (N); *b*=phosphoric acid (P_2O_5); *c*=potash (K_2O)]

Plot No.	Units of—		
	a	*b*	*c*
SERIES 1			
1	1	1	1
2	2	1	1
3	3	1	1
4	1	2	1
5	1	3	1
6	1	1	2
7	1	1	3
SERIES 2			
1	1	1	1
2	2	1	1
3	3	1	1
4	1	1	1
5	1	2	1
6	1	3	1
7	1	1	1
8	1	1	2
9	1	1	3
10	1	1	1
SERIES 3 [1]			
1	1	1	1
2	2	1	1
3	3	1	1
4	1	1	1
5	4	1	1
6	5	1	1
7	1	1	1
8	1	2	1
9	1	3	1
10	1	1	1
11	1	4	1
12	1	5	1
13	1	1	1
SERIES 3—Continued			
14	1	1	2
15	1	1	3
16	1	1	1
17	1	1	4
18	1	1	5
19	1	1	1
SERIES 4 [2]			
1	1	1	1
2	2	1	1
3	3	1	1
4	1	1	1
5	4	1	1
6	5	1	1
7	1	1	1
8	6	1	1
9	7	1	1
10	1	1	1
11	1	2	1
12	1	3	1
13	1	1	1
14	1	4	1
15	1	5	1
16	1	1	1
17	1	6	1
18	1	7	1
19	1	1	1
20	1	1	2
21	1	1	3
22	1	1	1
23	1	1	4
24	1	1	5
25	1	1	1
26	1	1	6
27	1	1	7
28	1	1	1
SERIES 5 [3]			
1	1	1	1
2	2	1	1
3	3	1	1
4	1	1	1
5	4	1	1
6	5	1	1
7	1	1	1
8	6	1	1
9	7	1	1
10	1	1	1
11	8	1	1
12	9	1	1
13	1	1	1
14	1	2	1
15	1	3	1
16	1	1	1
17	1	4	1
18	1	5	1
19	1	1	1
20	1	6	1
21	1	7	1
22	1	1	1
23	1	8	1
24	1	9	1
25	1	1	1
26	1	1	2
27	1	1	3
28	1	1	1
29	1	1	4
30	1	1	5
31	1	1	1
32	1	1	6
33	1	1	7
34	1	1	1
35	1	1	8
36	1	1	9
37	1	1	1

[1] Equivalent to 3 sets of series 2. [2] Equivalent to 5 sets of series 2. [3] Equivalent to 7 sets of series 2.

Series 1 of Table 17 may be called the fundamental series. It represents the absolute minimum of data required. In a preliminary note by the writer (*5*) a smaller number of plots was given as the minimum number required. At the time that note was written it was supposed that the values of R_1, R_2, and R_3, published by Mitscherlich, as indicated by Willcox (*10*), were generally applicable. It develops that they are not always applicable to the results of field experiments in the United States, so that it is necessary to determine the three R's of the equation for each case, along with the four other constants. But this series is devoid of check plots, and would have to be replicated many times to make the yields reliable.

Series 2 is similar to series 1, but in it every third plot is a check plot. These two series provide for the use of three different quantities of each growth factor. In use, it would require several replications of series 2 to give results sufficiently accurate.

Series 3, in which five different quantities of each variable element are used, is, from the standpoint of reliability of results, equivalent to three replications of series 2. Series 4 and 5 are, respectively, equivalent to five and seven replications of series 2. In careful experimental work series 4 (28 plots) would be about the minimum limit, and series 5 (37 plots) would give results considerably more reliable and is to be recommended. The discussion that follows is based on series 3 (19 plots) merely on grounds of economy of space. This series illustrates the principles involved as well as any other.

The plots in series 2 to 5 that receive 1 unit each of a, b, and c are the standard check plots, and constitute every third plot in each series. A check plot begins and ends each series. Experimenters often make every fourth plot a check plot. This reduces materially the usefulness of check plots. The added accuracy obtained by making every third plot a check is well worth while in most cases. In cases in which the soil is quite variable, and thus not well adapted to experimental-plot work, every second plot might well be a check.

The check plots in the series outlined are all fertilized, and the application is the same on all of them. The reason for this is that if the phenomenon of absorption of plant food by the soil is present, irregularities due to this phenomenon are thus avoided.

In cases in which it is desirable to measure the amount of this absorption, a separate group of plots for this purpose may be used. An outline of procedure in such cases is given later (p. 58).

USE OF CHECK PLOTS

Check plots are used in eliminating from the computations so far as possible, the effect of unevenness in the yielding power of the soil in different parts of the experimental field. These differences are adjusted in the following manner.

"Check yields" are computed for each plot. The check yield of a plot is the yield it would presumably have produced if it had had the same application of fertilizers as the check plots. The check yield of each check plot is, of course, the yield of the plot as recorded. The check yield of the series is the average of the check yields of the check plots. The check yield of the plots between check plots is the yield of the plot plus part of the difference between the adjacent check plots. In the 19-plot series, where every third plot is a check plot, the fractions are one-third for the plot next to the lower num-

bered check plot and two-thirds for the plot next to the higher numbered check plot. If three plots intervene between check plots, the fractions are one-fourth, one-half, and three-fourths.

This procedure assumes that the soil changes uniformly from one plot to the next. This is not strictly true, so that there is some error in the check yields. The error is greater the greater the number of plots between checks. Without check plots the experimental errors are often so great as to vitiate the results for any careful study.

In the 19-plot series the check yields are of the following description, plots 1 and 4 being check plots:

On plot 1, check yield (C_1) is the actual yield (y_1);
on plot 2, $C_2=y_2+\frac{1}{3}(y_4-y_1)$;
on plot 3, $C_3=y_3+\frac{2}{3}(y_4-y_1)$;
on plot 4, $C_4=y_4$;
on plot 5, $C_5=y_5+\frac{1}{3}(y_7-y_4)$; and so on through the series.

The check yields having been found, the relative yields of the plots are computed by dividing the actual yield of each plot by its check yield. For the check plots the relative yields are of course 1. Thus the relative yield (U_2) of plot 2 is U_2/C_2; of plot 3 it is U_3/C_3, and so on.

The "adjusted yields" of the several plots are computed by multiplying the check yield of the series (average of the yields on the check plots) by the relative yield of the plot. The adjusted yield of each check plot is the average of all of them taken together. These adjusted yields are the yields used in all subsequent calculations.

When some of the plant food applied is occluded by the soil, and it is desired to measure the amount of this occlusion, the data necessary to do this may be obtained by inserting plots in the series listed on page 56, as shown below.

If part of each of the three elements is occluded, insert in the series at the places indicated below, groups of 4 plots each, fertilized thus:

a	*b*	*c*	
1	1	1	check plot.
0	1	1	zero plot for N.
1	0	1	zero plot for P_2O_5.
1	1	0	zero plot for K_2O.

This group is to be inserted as follows: In series 2, (1) preceding plot 1, (2) between plots 3 and 4, (3) between plots 6 and 7. In series 3, (1) preceding plot 1; (2) between plots 6 and 7; and (3) between plots 12 and 13. In series 4, (1) preceding plot 1, (2) between plots 9 and 10, and (3) between plots 18 and 19; and so on.

If the occlusion does not affect any one of the plant-food elements, the zero plots for that element may be omitted.

These insertions will, of course, change the plot numbers throughout the series.

The average adjusted yields of the three zero plots for each element are taken as the yield when that element is omitted from the fertilizer. Insertion of the group of plots at three points in the series gives three replications for each zero plot.

OTHER FACTORS TO BE CONSIDERED

This bulletin deals only with the relation between plant growth and the quantity of nitrogen, phosphoric acid, and potash available to the growing crop. Many other factors affect the growth of plants,

such as soil acidity, magnesium, sulphur, the organic matter of the soil, tilth, date of planting, amount of sunlight, length of day, availability of soil moisture, texture of the soil, and temperature.

Some of these factors have been shown to produce yield curves similar to those discussed herein. This is the case with sunlight and soil moisture. Whether others behave in a similar manner remains for further research to reveal.

Additional factors that do produce yield curves similar to those dealt with here may be taken into account by adding to the generalized yield equation a factor of the form $(1-R^x)$ for each additional growth factor, and by adding to the list of experimental plots for each new growth factor a series of plots in which the new growth factor is varied in the same way as nitrogen, phosphoric acid, and potash are varied in the series listed.

SUMMARY

Three methods are given for determining the constants of the exponential yield equation for a single variable growth factor. One of these methods makes possible the determination of the most probable value of the constants by the method of least squares.

A method of determining the amount of available plant food in the soil is outlined.

The application of the exponential yield curve to a specific case in which each of the three common plant-food elements is varied is given, including the method of passing from the 1-variable form to the general form of the equation.

A method is presented for determining the amount, if any, of each of the three common plant-food elements absorbed by the soil and held in a condition unavailable to the growing crop.

The form of the yield curve is discussed, and reasons given for preferring the exponential to the parabolic form.

The derivation of all the commonly employed forms of the exponential yield curve is presented.

Formulas are worked out for determining for specific cases the optimum fertilizer formula to use, the optimum quantity of fertilizer to apply for greatest profit per acre, and for determining the optimum formula to use and the optimum acreage to which to apply a fixed amount (value) of fertilizer for greatest profit per dollar invested in fertilizer, in both presence and absence of the phenomenon of plant-food occlusion by the soil.

Plans are outlined for obtaining, from a relatively small number of experimental plots, the data necessary for determining the constants in the exponential yield equation, and the manner of utilizing check plots as a means of eliminating, in so far as this can be done, unevenness in the yielding power of the soil of the experimental field is discussed.

APPENDIX

TABLES OF VALUES OF R^x AND OF $1-R^x$

Tables 18 and 19 are appended because of their great usefulness in computations of the character required in work of the type outlined in this bulletin.

Table 18 gives the values of R^x for all values of R from 0.01 to 0.99 and of x from zero to 20. A given power of a given value of R stands on line with the value of R in the left-hand column of the page, in the column headed by the index of the power.

This table was computed by Y. Kutsunai, of the Hawaiian Sugar Experiment Station.

For convenience in computation a table of values of $1-R^x$ has been prepared on the basis of $R=0.8$, between $x=0$ and $x=29.99$. (Table 19.) Higher values of x rarely occur in connection with the yield equation.

As explained in the text, conversion of the actual ratio of the problem in hand to the ratio 0.8 is readily made.

To find $1-R^x$ when $x=3.27$, for example, run down the left-hand column of page 63 to the line showing the integral and first decimal place of x (3.2) and read the value in the column headed by the figure in the second decimal place (7). This is stated as 51794 and is a decimal fraction, all decimal points having been omitted in the printing.

To find x when $1-R^x$ is obtained in the computations, find the $1-R^x$ in the table nearest to the figure obtained and read the value of x. Thus x nearest corresponding to $1-R^x=0.57266$ is found in the column headed 1 on line 3.8, so that x in this case is 3.81. Ordinarily it is not necessary to carry the value of x beyond the second decimal place. Additional decimal places are found by interpolation; the further decimal places are the quotient of the excess above the lower tabular number divided by the tabular difference.

R^x (when $R=0.8$) may be found by subtracting the table figure for $1-R^x$ from 1.00000.

TABLE 18.—*Values of* R^x

[Value of $x=0$ is 1 in all cases; of $x=1$, same as R]

R	$x=2$	$x=3$	$x=4$	$x=5$	$x=6$	$x=7$	$x=8$	$x=9$	$x=10$	$x=11$
0. 01	0. 0001	0. 000001								
. 02	. 0004	. 000008								
. 03	. 0009	. 000027	0. 000001							
. 04	. 0016	. 000064	. 000003							
. 05	. 0025	. 000125	. 000006							
. 06	. 0036	. 000216	. 000013	0. 000001						
. 07	. 0049	. 000343	. 000024	. 000002						
. 08	. 0064	. 000512	. 000041	. 000003						
. 09	. 0081	. 000729	. 000066	. 000006	0. 000001					
. 10	. 0100	. 001000	. 000100	. 000010	. 000001					
. 11	. 0121	. 001331	. 000146	. 000016	. 000002					
. 12	. 0144	. 001728	. 000207	. 000025	. 000003					
. 13	. 0169	. 002197	. 000286	. 000037	. 000005	0. 000001				
. 14	. 0196	. 002744	. 000384	. 000054	. 000008	. 000001				
. 15	. 0225	. 003375	. 000506	. 000076	. 000011	. 000002				
. 16	. 0256	. 004096	. 000655	. 000105	. 000017	. 000003				
. 17	. 0289	. 004913	. 000835	. 000142	. 000024	. 000004	0. 000001			
. 18	. 0324	. 005832	. 001050	. 000189	. 000034	. 000006	. 000001			
. 19	. 0361	. 006859	. 001303	. 000248	. 000047	. 000009	. 000002			
. 20	. 0400	. 008000	. 001600	. 000320	. 000064	. 000013	. 000003	0. 000001		
. 21	. 0441	. 009261	. 001945	. 000408	. 000086	. 000018	. 000004	. 000001		
. 22	. 0484	. 010648	. 002343	. 000515	. 000113	. 000025	. 000005	. 000001		
. 23	. 0529	. 012167	. 002798	. 000644	. 000148	. 000034	. 000008	. 000002		
. 24	. 0576	. 013824	. 003318	. 000796	. 000191	. 000046	. 000011	. 000003	0. 000001	
. 25	. 0625	. 015625	. 003906	. 000977	. 000244	. 000061	. 000015	. 000004	. 000001	
. 26	. 0676	. 017576	. 004570	. 001188	. 000309	. 000080	. 000021	. 000005	. 000001	
. 27	. 0729	. 019683	. 005314	. 001435	. 000387	. 000105	. 000028	. 000008	. 000002	0. 000001
. 28	. 0784	. 021952	. 006147	. 001721	. 000482	. 000135	. 000038	. 000011	. 000003	. 000001
. 29	. 0841	. 024389	. 007073	. 002051	. 000595	. 000172	. 000050	. 000015	. 000004	. 000001
. 30	. 0900	. 027000	. 008100	. 002430	. 000729	. 000219	. 000066	. 000020	. 000006	. 000002
. 31	. 0961	. 029791	. 009235	. 002863	. 000888	. 000275	. 000085	. 000026	. 000008	. 000003
. 32	. 1024	. 032768	. 010486	. 003355	. 001074	. 000344	. 000110	. 000035	. 000011	. 000004
. 33	. 1089	. 035937	. 011859	. 003914	. 001291	. 000426	. 000141	. 000046	. 000015	. 000005
. 34	. 1156	. 039304	. 013363	. 004544	. 001545	. 000525	. 000179	. 000061	. 000021	. 000007
. 35	. 1225	. 042875	. 015006	. 005252	. 001838	. 000643	. 000225	. 000079	. 000028	. 000010
. 36	. 1296	. 046656	. 016796	. 006047	. 002177	. 000784	. 000282	. 000102	. 000037	. 000013
. 37	. 1369	. 050653	. 018742	. 006934	. 002566	. 000949	. 000351	. 000130	. 000048	. 000018
. 38	. 1444	. 054872	. 020851	. 007924	. 003011	. 001144	. 000435	. 000165	. 000063	. 000024
. 39	. 1521	. 059319	. 023134	. 009022	. 003519	. 001372	. 000535	. 000209	. 000081	. 000032
. 40	. 1600	. 064000	. 025600	. 010240	. 004096	. 001638	. 000655	. 000262	. 000105	. 000042
. 41	. 1681	. 068921	. 028258	. 011586	. 004750	. 001948	. 000798	. 000327	. 000134	. 000055
. 42	. 1764	. 074088	. 031117	. 013069	. 005489	. 002305	. 000968	. 000407	. 000171	. 000072
. 43	. 1849	. 079507	. 034188	. 014701	. 006321	. 002718	. 001169	. 000503	. 000216	. 000093
. 44	. 1936	. 085184	. 037481	. 016492	. 007256	. 003193	. 001405	. 000618	. 000272	. 000120
. 45	. 2025	. 091125	. 041006	. 018453	. 008304	. 003737	. 001682	. 000757	. 000341	. 000153
. 46	. 2116	. 097336	. 044775	. 020596	. 009474	. 004358	. 002005	. 000922	. 000424	. 000195
. 47	. 2209	. 103823	. 048797	. 022935	. 010779	. 005066	. 002381	. 001119	. 000526	. 000247
. 48	. 2304	. 110592	. 053084	. 025480	. 012231	. 005871	. 002818	. 001353	. 000649	. 000312
. 49	. 2401	. 117649	. 057648	. 028248	. 013841	. 006782	. 003323	. 001628	. 000798	. 000391
. 50	. 2500	. 125000	. 062500	. 031250	. 015625	. 007813	. 003906	. 001953	. 000977	. 000488
. 51	. 2601	. 132651	. 067652	. 034503	. 017596	. 008974	. 004577	. 002334	. 001190	. 000607
. 52	. 2704	. 140608	. 073116	. 038020	. 019771	. 010281	. 005346	. 002780	. 001446	. 000752
. 53	. 2809	. 148877	. 078905	. 041820	. 022164	. 011747	. 006226	. 003300	. 001749	. 000927

TABLE 18.—*Values of* R^x—Continued

R	$x=2$	$x=3$	$x=4$	$x=5$	$x=6$	$x=7$	$x=8$	$x=9$	$x=10$	$x=11$
0.54	0.2916	0.157464	0.085031	0.045917	0.024795	0.013389	0.007230	0.003904	0.002108	0.001138
.55	.3025	.166375	.091506	.050328	.027681	.015224	.008373	.004605	.002533	.001393
.56	.3136	.175616	.098345	.055073	.030841	.017271	.009672	.005416	.003033	.001699
.57	.3249	.185193	.105560	.060169	.034296	.019549	.011143	.006351	.003620	.002064
.58	.3364	.195112	.113165	.065636	.038069	.022080	.012806	.007428	.004308	.002499
.59	.3481	.205379	.121174	.071492	.042181	.024887	.014683	.008663	.005111	.003016
.60	.3600	.216000	.129600	.077760	.046656	.027994	.016796	.010078	.006047	.003628
.61	.3721	.226981	.138458	.084460	.051520	.031427	.019171	.011694	.007133	.004351
.62	.3844	.238328	.147763	.091613	.056800	.035216	.021834	.013537	.008393	.005204
.63	.3969	.250047	.157530	.099244	.062524	.039390	.024816	.015634	.009849	.006205
.64	.4096	.262144	.167772	.107374	.068719	.043980	.028147	.018014	.011529	.007379
.65	.4225	.274625	.178506	.116029	.075419	.049022	.031864	.020712	.013463	.008751
.66	.4356	.287496	.189747	.125233	.082654	.054552	.036004	.023763	.015683	.010351
.67	.4489	.300763	.201511	.135013	.090458	.060607	.040607	.027207	.018228	.012213
.68	.4624	.314432	.213814	.145393	.098867	.067230	.045716	.031087	.021139	.014375
.69	.4761	.328509	.226671	.156403	.107918	.074464	.051380	.035452	.024462	.016879
.70	.4900	.343000	.240100	.168070	.117649	.082354	.057648	.040354	.028248	.019773
.71	.5041	.357911	.254117	.180423	.128100	.090951	.064575	.045849	.032552	.023112
.72	.5184	.373248	.268739	.193492	.139314	.100306	.072220	.051999	.037439	.026956
.73	.5329	.389017	.283982	.207307	.151334	.110474	.080646	.058872	.042976	.031373
.74	.5476	.405224	.299866	.221901	.164206	.121513	.089919	.066540	.049240	.036438
.75	.5625	.421875	.316406	.237305	.177979	.133484	.100113	.075085	.056314	.042235
.76	.5776	.438976	.333622	.253553	.192700	.146452	.111303	.084591	.064289	.048860
.77	.5929	.456533	.351530	.270678	.208422	.160485	.123574	.095152	.073267	.056415
.78	.6084	.474552	.370151	.288717	.225200	.175656	.137011	.106869	.083358	.065019
.79	.6241	.493039	.389501	.307706	.243087	.192039	.151711	.119852	.094683	.074799
.80	.6400	.512000	.409600	.327680	.262144	.209715	.167772	.134218	.107374	.085899
.81	.6561	.531441	.430467	.348678	.282430	.228768	.185302	.150095	.121577	.098477
.82	.6724	.551368	.452122	.370740	.304007	.249285	.204414	.167620	.137448	.112707
.83	.6889	.571787	.474583	.393904	.326940	.271361	.225229	.186940	.155160	.128783
.84	.7056	.592704	.497871	.418212	.351298	.295090	.247876	.208216	.174901	.146917
.85	.7225	.614125	.522006	.443705	.377150	.320577	.272491	.231617	.196874	.167343
.86	.7396	.636056	.547008	.470427	.404567	.347928	.299218	.257327	.221302	.190319
.87	.7569	.658503	.572898	.498421	.433626	.377255	.328212	.285544	.248423	.216128
.88	.7744	.681472	.599695	.527732	.464404	.408676	.359635	.316478	.278501	.245081
.89	.7921	.704969	.627422	.558406	.496981	.442313	.393659	.350356	.311817	.277517
.90	.8100	.729000	.656100	.590490	.531441	.478297	.430467	.387420	.348678	.313811
.91	.8281	.753571	.685750	.624032	.567869	.516751	.470253	.427930	.389416	.354309
.92	.8464	.778688	.716393	.659082	.606355	.557847	.513219	.472161	.434388	.399637
.93	.8649	.804357	.748052	.695688	.646990	.601701	.559582	.520411	.483982	.450104
.94	.8836	.830584	.780749	.733904	.689870	.648478	.609569	.572995	.538615	.506298
.95	.9025	.857375	.814506	.773781	.735092	.698337	.663420	.630249	.598737	.568800
.96	.9216	.884736	.849347	.815373	.782758	.751447	.721390	.692534	.664833	.638239
.97	.9409	.912673	.885293	.858734	.832972	.807983	.783743	.760231	.737424	.715301
.98	.9604	.941192	.922368	.903921	.885842	.868126	.850763	.833748	.817073	.800731
.99	.9801	.970299	.960596	.950990	.941480	.932065	.922745	.913517	.904382	.895338

R	$x=12$	$x=13$	$x=14$	$x=15$	$x=16$	$x=17$	$x=18$	$x=19$	$x=20$
0.30	0.000001								
.31	.000001								
.32	.000001								
.33	.000002	0.000001							
.34	.000002	.000001							
.35	.000003	.000001							
.36	.000005	.000002	0.000001						
.37	.000007	.000002	.000001						
.38	.000009	.000003	.000001						
.39	.000012	.000005	.000002	0.000001					
.40	.000017	.000007	.000003	.000001					
.41	.000023	.000009	.000004	.000002	0.000001				
.42	.000030	.000013	.000005	.000002	.000001				
.43	.000040	.000017	.000007	.000003	.000001	0.000001			
.44	.000053	.000023	.000010	.000004	.000002	.000001			
.45	.000069	.000031	.000014	.000006	.000003	.000001	0.000001		
.46	.000090	.000041	.000019	.000009	.000004	.000002	.000001		
.47	.000116	.000055	.000026	.000012	.000006	.000003	.000001	0.000001	
.48	.000150	.000072	.000034	.000017	.000008	.000004	.000002	.000001	
.49	.000192	.000094	.000046	.000023	.000011	.000005	.000003	.000001	0.000001
.50	.000244	.000122	.000061	.000031	.000015	.000008	.000004	.000002	.000001
.51	.000310	.000158	.000081	.000041	.000021	.000011	.000005	.000003	.000001
.52	.000391	.000203	.000106	.000055	.000029	.000015	.000008	.000004	.000002
.53	.000491	.000260	.000138	.000073	.000039	.000021	.000011	.000006	.000003
.54	.000615	.000332	.000179	.000097	.000052	.000028	.000015	.000008	.000004
.55	.000766	.000421	.000232	.000127	.000070	.000039	.000021	.000012	.000006
.56	.000951	.000533	.000298	.000167	.000094	.000052	.000029	.000016	.000009
.57	.001176	.000670	.000382	.000218	.000124	.000071	.000040	.000023	.000013
.58	.001449	.000841	.000488	.000283	.000164	.000095	.000055	.000032	.000019
.59	.001779	.001050	.000619	.000365	.000216	.000127	.000075	.000044	.000026
.60	.002177	.001306	.000784	.000470	.000282	.000169	.000102	.000061	.000037

TABLE 18.—*Values of* R^x—Continued

R	$x=12$	$x=13$	$x=14$	$x=15$	$x=16$	$x=17$	$x=18$	$x=19$	$x=20$
0.61	0.002654	0.001619	0.000988	0.000602	0.000368	0.000224	0.000137	0.000083	0.000051
.62	.003226	.002000	.001240	.000769	.000477	.000296	.000183	.000114	.000070
.63	.003909	.002463	.001552	.000977	.000616	.000388	.000244	.000154	.000099
.64	.004722	.003022	.001934	.001238	.000792	.000507	.000325	.000208	.000133
.65	.005688	.003697	.002403	.001562	.001015	.000660	.000429	.000279	.000181
.66	.006832	.004509	.002976	.001964	.001296	.000856	.000565	.000373	.000246
.67	.008183	.005482	.003673	.002461	.001649	.001105	.000740	.000496	.000332
.68	.009775	.006647	.004520	.003074	.002090	.001421	.000966	.000657	.000447
.69	.011646	.008036	.005545	.003826	.002640	.001822	.001257	.000867	.000598
.70	.013841	.009689	.006782	.004748	.003323	.002326	.001628	.001140	.000798
.71	.016410	.011651	.008272	.005873	.004170	.002961	.002102	.001492	.001060
.72	.019408	.013974	.010061	.007244	.005216	.003755	.002704	.001947	.001402
.73	.022902	.016718	.012205	.008909	.006504	.004748	.003466	.002530	.001847
.74	.026964	.019953	.014765	.010926	.008086	.005983	.004428	.003276	.002425
.75	.031676	.023757	.017818	.013363	.010023	.007517	.005638	.004228	.003171
.76	.037133	.028221	.021448	.016301	.012388	.009415	.007156	.005438	.004133
.77	.043440	.033449	.025756	.019832	.015270	.011758	.009054	.006971	.005368
.78	.050715	.039558	.030855	.024067	.018772	.014642	.011421	.008908	.006949
.79	.059092	.046682	.036879	.029134	.023016	.018183	.014364	.011348	.008965
.80	.068719	.054976	.043980	.035184	.028147	.022518	.018014	.014412	.011529
.81	.079766	.064611	.052335	.042391	.034337	.027813	.022528	.018248	.014781
.82	.092420	.075784	.062143	.050957	.041785	.034264	.028096	.023039	.018892
.83	.106890	.088719	.073637	.061118	.050728	.042104	.034947	.029006	.024075
.84	.123410	.103665	.087078	.073146	.061442	.051612	.043354	.036417	.030590
.85	.142242	.120905	.102770	.087354	.074251	.063113	.053646	.045599	.038760
.86	.163675	.140760	.121054	.104106	.089531	.076997	.066217	.056947	.048974
.87	.188032	.163588	.142321	.123819	.107723	.093719	.081535	.070936	.061714
.88	.215671	.189791	.167016	.146974	.129337	.113817	.100159	.088140	.077563
.89	.246990	.219821	.195641	.174121	.154967	.137921	.122750	.109247	.097230
.90	.282430	.254187	.228768	.205891	.185302	.166772	.150095	.135085	.121577
.91	.322475	.293453	.267042	.243008	.221137	.201235	.183124	.166643	.151645
.92	.367666	.338253	.311193	.286297	.263394	.242322	.222936	.205101	.188693
.93	.418596	.389295	.362044	.336701	.313132	.291213	.270828	.251870	.234239
.94	.475920	.447365	.420523	.395202	.371574	.349280	.328323	.308624	.290106
.95	.540360	.513342	.487675	.463291	.440127	.418120	.397214	.377354	.358486
.96	.612710	.588201	.564673	.542086	.520403	.499587	.479603	.460419	.442002
.97	.693842	.673027	.652836	.633251	.614254	.595826	.577951	.560613	.543794
.98	.784717	.769022	.753642	.738569	.723798	.709322	.695135	.681233	.667608
.99	.886385	.877521	.868746	.860058	.851458	.842943	.834514	.826169	.817907

TABLE 19.—*Values of* $1-R^x$ *when* $R=0.8$

[All values are decimal fractions; that is, decimal points to be added]

x	0	1	2	3	4	5	6	7	8	9
0.0	00000	00223	00445	00667	00889	01110	01330	01550	01769	01988
.1	02207	02425	02642	02859	03076	03292	03507	03722	03937	04151
.2	04365	04578	04791	05003	05215	05426	05637	05847	06057	06266
.3	06475	06684	06892	07099	07306	07513	07719	07925	08130	08335
.4	08539	08743	08946	09149	09352	09554	09755	09956	10157	10357
.5	10557	10757	10956	11154	11352	11550	11747	11944	12140	12336
.6	12531	12726	12920	13114	13308	13501	13694	13887	14079	14270
.7	14461	14652	14842	15032	15221	15410	15599	15787	15975	16162
.8	16349	16535	16721	16907	17092	17277	17461	17645	17829	18012
.9	18195	18377	18559	18741	18922	19102	19283	19463	19642	19821
1.0	20000	20178	20356	20534	20711	20888	21064	21240	21415	21590
1.1	21765	21940	22114	22287	22461	22634	22806	22978	23150	23321
1.2	23492	23662	23832	24002	24172	24341	24509	24677	24845	25013
1.3	25180	25347	25513	25679	25845	26010	26176	26340	26504	26668
1.4	26831	26994	27157	27319	27481	27643	27804	27965	28126	28286
1.5	28446	28605	28764	28923	29082	29240	29397	29555	29712	29869
1.6	30025	30181	30336	30492	30647	30801	30955	31109	31263	31416
1.7	31569	31722	31874	32026	32177	32328	32479	32630	32780	32930
1.8	33079	33228	33377	33526	33674	33822	33969	34116	34263	34410
1.9	34556	34702	34847	34992	35137	35282	35426	35570	35714	35857
2.0	36000	36143	36285	36427	36569	36710	36851	36992	37132	37272
2.1	37412	37552	37691	37830	37968	38106	38244	38382	38520	38657
2.2	38793	38930	39066	39202	39337	39472	39607	39742	39876	40010
2.3	40144	40277	40410	40543	40676	40808	40940	41072	41203	41334
2.4	41465	41595	41725	41855	41985	42114	42243	42372	42501	42629
2.5	42757	42884	43012	43139	43265	43392	43518	43644	43769	43895
2.6	44020	44145	44269	44393	44517	44641	44764	44887	45010	45133
2.7	45255	45377	45499	45620	45742	45863	45983	46104	46224	46344
2.8	46463	46583	46702	46820	46939	47057	47175	47293	47410	47528
2.9	47645	47761	47878	47994	48110	48226	48341	48456	48571	48686
3.0	48800	48914	49028	49141	49255	49368	49481	49594	49706	49818
3.1	49930	50042	50153	50264	50375	50485	50596	50706	50816	50925

TABLE 19.—*Values of* $1-R^x$ *when* $R=0.8$—Continued

x	0	1	2	3	4	5	6	7	8	9
3.2	51035	51144	51253	51361	51470	51578	51686	51794	51901	52008
3.3	52115	52222	52329	52435	52541	52647	52752	52857	52962	53067
3.4	53172	53276	53380	53484	53588	53692	53795	53898	54000	54103
3.5	54205	54307	54409	54511	54612	54713	54814	54915	55016	55116
3.6	55216	55316	55415	55515	55614	55713	55811	55910	56008	56106
3.7	56204	56302	56399	56496	56593	56690	56787	56883	56979	57075
3.8	57171	57266	57361	57456	57551	57646	57740	57834	57928	58022
3.9	58116	58209	58302	58395	58488	58580	58673	58765	58857	58948
4.0	59040	59131	59222	59313	59404	59494	59585	59675	59765	59854
4.1	59944	60033	60122	60211	60300	60388	60477	60565	60653	60740
4.2	60828	60915	61002	61089	61176	61262	61349	61435	61521	61607
4.3	61692	61778	61863	61948	62033	62117	62202	62286	62370	62454
4.4	62538	62621	62704	62788	62870	62953	63036	63118	63200	63282
4.5	63364	63446	63527	63609	63690	63771	63851	63932	64012	64093
4.6	64173	64253	64332	64412	64491	64570	64649	64728	64807	64885
4.7	64963	65041	65119	65197	65275	65352	65429	65506	65583	65660
4.8	65736	65813	65889	65965	66041	66117	66192	66268	66343	66418
4.9	66493	66567	66642	66716	66790	66864	66938	67012	67085	67159
5.0	67232	67305	67378	67451	67523	67596	67668	67740	67812	67883
5.1	67955	68027	68098	68169	68240	68311	68381	68451	68522	68592
5.2	68662	68732	68802	68871	68941	69010	69079	69148	69217	69285
5.3	69354	69422	69490	69558	69626	69694	69761	69829	69896	69963
5.4	70030	70097	70164	70230	70296	70363	70429	70495	70560	70626
5.5	70691	70757	70822	70887	70952	71016	71081	71146	71210	71274
5.6	71338	71402	71466	71529	71592	71656	71719	71782	71845	71908
5.7	71971	72033	72095	72158	72220	72282	72344	72406	72467	72528
5.8	72589	72650	72711	72772	72833	72893	72954	73014	73074	73134
5.9	73194	73254	73313	73373	73432	73491	73551	73610	73668	73727
6.0	73786	73844	73902	73960	74018	74076	74134	74192	74249	74307
6.1	74364	74421	74478	74535	74592	74649	74705	74761	74818	74874
6.2	74930	74986	75041	75097	75153	75208	75263	75318	75373	75428
6.3	75483	75538	75592	75647	75701	75755	75809	75863	75917	75970
6.4	76024	76077	76131	76184	76237	76290	76343	76396	76448	76501
6.5	76553	76605	76658	76710	76761	76813	76865	76917	76968	77019
6.6	77071	77122	77173	77224	77274	77325	77375	77426	77476	77526
6.7	77578	77626	77676	77726	77776	77825	77875	77924	77973	78022
6.8	78071	78120	78169	78218	78266	78315	78363	78411	78459	78507
6.9	78556	78603	78651	78698	78746	78793	78840	78888	78935	78982
7.0	79028	79075	79122	79168	79215	79261	79307	79354	79400	79445
7.1	79491	79537	79583	79628	79674	79719	79764	79809	79854	79899
7.2	79944	79989	80033	80078	80122	80166	80211	80255	80299	80343
7.3	80386	80430	80474	80517	80561	80604	80647	80690	80733	80776
7.4	80819	80862	80905	80947	80990	81032	81074	81117	81159	81201
7.5	81242	81284	81326	81367	81409	81451	81492	81533	81574	81615
7.6	81656	81697	81738	81779	81819	81860	81900	81941	81981	82021
7.7	82061	82101	82141	82181	82221	82260	82300	82339	82379	82418
7.8	82457	82496	82535	82574	82613	82652	82690	82729	82768	82806
7.9	82844	82882	82920	82959	82997	83035	83072	83110	83148	83185
8.0	83223	83260	83297	83335	83372	83409	83446	83483	83520	83557
8.1	83593	83630	83666	83702	83739	83775	83811	83847	83883	83919
8.2	83955	83991	84027	84062	84098	84133	84168	84204	84239	84274
8.3	84309	84344	84379	84414	84449	84483	84518	84552	84587	84621
8.4	84655	84690	84724	84758	84792	84826	84859	84893	84927	84960
8.5	84994	85027	85061	85094	85127	85161	85194	85227	85259	85292
8.6	85325	85358	85391	85423	85456	85488	85520	85552	85585	85617
8.7	85649	85681	85713	85745	85776	85808	85840	85872	85903	85934
8.8	85966	85997	86028	86059	86090	86121	86152	86183	86214	86245
8.9	86274	86306	86336	86367	86397	86428	86458	86488	86518	86548
9.0	86578	86608	86638	86668	86697	86727	86757	86786	86816	86845
9.1	86875	86904	86933	86962	86991	87018	87049	87078	87107	87136
9.2	87164	87193	87221	87250	87278	87306	87335	87363	87391	87419
9.3	87447	87475	87503	87531	87559	87587	87614	87642	87669	87697
9.4	87724	87752	87779	87806	87833	87860	87887	87915	87942	87968
9.5	87995	88022	88049	88075	88102	88128	88155	88181	88208	88234
9.6	88260	88286	88312	88338	88364	88390	88416	88442	88468	88494
9.7	88519	88545	88570	88596	88621	88647	88672	88697	88722	88747
9.8	88773	88798	88823	88847	88872	88897	88922	88947	88971	88996
9.9	89020	89045	89069	89094	89118	89142	89166	89190	89215	89239
10.0	89263	89287	89310	89334	89358	89382	89405	89429	89453	89476
10.1	89500	89523	89546	89570	89593	89616	89639	89662	89685	89708
10.2	89731	89754	89777	89800	89822	89845	89868	89890	89913	89936
10.3	89958	89980	90003	90025	90047	90069	90091	90113	90135	90157
10.4	90179	90201	90223	90245	90267	90288	90310	90332	90353	90375
10.5	90396	90418	90439	90460	90482	90503	90524	90545	90566	90587
10.6	90608	90629	90650	90671	90692	90712	90733	90754	90774	90795
10.7	90815	90836	90856	90877	90897	90917	90937	90958	90978	90998
10.8	91018	91038	91058	91078	91098	91118	91138	91157	91177	91197
10.9	91216	91236	91255	91275	91294	91314	91333	91352	91372	91391
11.0	91410	91429	91448	91467	91486	91505	91524	91543	91562	91581
11.1	91600	91618	91637	91656	91674	91693	91711	91730	91748	91767
11.2	91785	91803	91822	91840	91858	91876	91894	91912	91930	91948
11.3	91966	91984	92002	92020	92038	92055	92073	92091	92108	92126
11.4	92144	92161	92179	92196	92213	92231	92248	92265	92283	92300

TABLE 19.—*Values of* $1-R^x$ *when* $R=0.8$—Continued

x	0	1	2	3	4	5	6	7	8	9
11.5	92317	92334	92351	92368	92385	92402	92419	92436	92453	92470
11.6	92487	92503	92520	92537	92553	92570	92586	92603	92619	92636
11.7	92652	92669	92685	92701	92718	92734	92750	92766	92782	92798
11.8	92814	92830	92846	92862	92878	92894	92910	92926	92942	92957
11.9	92973	92989	93004	93020	93035	93051	93066	93082	93097	93113
12.0	93128	93143	93159	93174	93189	93204	93219	93235	93250	93265
12.1	93280	93295	93310	93324	93339	93354	93369	93384	93399	93413
12.2	93428	93443	93457	93472	93486	93501	93515	93530	93544	93559
12.3	93573	93587	93602	93616	93630	93644	93658	93673	93687	93701
12.4	93715	93729	93743	93757	93771	93785	93798	93812	93826	93840
12.5	93853	93867	93881	93895	93908	93922	93935	93949	93962	93976
12.6	93989	94003	94016	94029	94043	94056	94069	94082	94095	94109
12.7	94122	94135	94148	94161	94174	94187	94200	94213	94226	94239
12.8	94252	94264	94277	94290	94303	94315	94328	94341	94353	94366
12.9	94378	94391	94403	94416	94428	94441	94453	94465	94478	94490
13.0	94502	94515	94527	94539	94551	94563	94575	94588	94600	94612
13.1	94624	94636	94648	94660	94671	94683	94695	94707	94719	94731
13.2	94742	94754	94766	94777	94789	94801	94812	94824	94835	94847
13.3	94858	94870	94881	94893	94904	94915	94927	94938	94949	94961
13.4	94972	94983	94994	95005	95017	95028	95039	95050	95061	95072
13.5	95083	95094	95105	95116	95126	95137	95148	95159	95170	95181
13.6	95191	95202	95213	95223	95234	95245	95255	95266	95276	95287
13.7	95297	95308	95318	95329	95339	95349	95360	95370	95381	95391
13.8	95401	95411	95422	95432	95442	95452	95462	95472	95483	95493
13.9	95503	95513	95523	95533	95543	95553	95563	95572	95582	95592
14.0	95602	95612	95621	95631	95641	95651	95660	95670	95680	95689
14.1	95699	95709	95718	95728	95737	95747	95756	95766	95775	95784
14.2	95794	95803	95813	95822	95831	95841	95850	95859	95868	95878
14.3	95887	95896	95905	95914	95923	95932	95941	95951	95960	95969
14.4	95978	95987	95995	96004	96013	96022	96031	96040	96049	96058
14.5	96066	96075	96084	96092	96101	96110	96119	96127	96136	96144
14.6	96153	96162	96170	96179	96187	96196	96204	96213	96221	96230
14.7	96238	96246	96255	96263	96271	96280	96288	96296	96304	96313
14.8	96321	96329	96337	96346	96354	96362	96370	96378	96386	96393
14.9	96402	96410	96418	96426	96434	96442	96450	96458	96466	96474
15.0	96482	96489	96497	96505	96513	96521	96528	96536	96544	96551
15.1	96559	96567	96574	96582	96590	96597	96605	96612	96620	96628
15.2	96635	96643	96650	96658	96665	96672	96680	96687	96695	96702
15.3	96709	96717	96724	96731	96739	96746	96753	96760	96768	96775
15.4	96782	96789	96796	96803	96811	96818	96825	96832	96839	96846
15.5	96853	96860	96867	96874	96881	96888	96895	96902	96909	96916
15.6	96923	96929	96936	96943	96950	96957	96963	96970	96977	96984
15.7	96991	96998	97004	97010	97017	97024	97030	97037	97044	97050
15.8	97057	97063	97070	97076	97083	97089	97096	97102	97109	97115
15.9	97122	97128	97135	97141	97147	97154	97160	97166	97173	97179
16.0	97185	97192	97198	97204	97210	97216	97223	97229	97235	97241
16.1	97247	97253	97260	97266	97272	97278	97284	97290	97296	97302
16.2	97308	97314	97320	97326	97332	97338	97344	97350	97356	97362
16.3	97368	97373	97379	97385	97391	97397	97403	97408	97414	97420
16.4	97426	97431	97437	97443	97448	97454	97460	97465	97471	97477
16.5	97482	97488	97494	97499	97505	97510	97516	97521	97527	97532
16.6	97538	97544	97549	97554	97560	97565	97571	97576	97581	97587
16.7	97592	97598	97603	97608	97614	97619	97624	97630	97635	97640
16.8	97645	97651	97656	97661	97666	97671	97677	97682	97687	97692
16.9	97697	97702	97708	97713	97718	97723	97728	97733	97738	97743
17.0	97748	97753	97758	97763	97768	97773	97778	97783	97788	97793
17.1	97798	97803	97808	97813	97817	97822	97827	97832	97837	97842
17.2	97846	97851	97856	97861	97866	97870	97875	97880	97885	97889
17.3	97894	97899	97903	97908	97913	97917	97922	97927	97931	97936
17.4	97940	97945	97950	97954	97959	97963	97968	97972	97977	97981
17.5	97986	97990	97995	97999	98004	98008	98013	98017	98022	98026
17.6	98030	98035	98039	98043	98048	98052	98056	98061	98065	98069
17.7	98074	98078	98082	98087	98091	98095	98099	98104	98108	98112
17.8	98116	98120	98125	98129	98133	98137	98141	98146	98150	98154
17.9	98158	98162	98166	98170	98174	98178	98182	98186	98190	98194
18.0	98199	98203	98207	98211	98215	98219	98223	98226	98230	98234
18.1	98238	98242	98246	98250	98254	98258	98262	98266	98269	98273
18.2	98277	98281	98285	98289	98292	98296	98300	98304	98308	98311
18.3	98315	98319	98323	98326	98330	98334	98338	98341	98345	98349
18.4	98352	98356	98360	98363	98367	98371	98374	98378	98382	98385
18.5	98389	98392	98396	98399	98403	98406	98410	98414	98417	98421
18.6	98424	98428	98431	98435	98438	98442	98445	98449	98452	98456
18.7	98459	98462	98466	98469	98472	98476	98480	98483	98486	98490
18.8	98494	98497	98500	98503	98506	98510	98513	98516	98520	98523
18.9	98526	98530	98533	98536	98539	98543	98546	98549	98552	98556
19.0	98559	98562	98565	98568	98572	98575	98578	98581	98584	98587
19.1	98591	98594	98597	98600	98603	98606	98609	98612	98616	98619
19.2	98622	98625	98628	98631	98634	98637	98640	98643	98646	98649
19.3	98652	98655	98658	98661	98664	98667	98670	98673	98676	98679
19.4	98682	98685	98688	98691	98694	98697	98699	98702	98705	98708
19.5	98711	98714	98717	98720	98722	98725	98728	98731	98734	98737
19.6	98739	98742	98745	98748	98751	98753	98756	98759	98762	98765
19.7	98767	98770	98773	98775	98778	98781	98784	98786	98789	98792

TABLE 19.—*Values of* $1-R^x$ *when* $R=0.8$—Continued

x	0	1	2	3	4	5	6	7	8	9
19.8	98794	98797	98800	98802	98805	98808	98810	98813	98816	98819
19.9	98821	98824	98826	98829	98832	98834	98837	98839	98842	98845
20.0	98847	98850	98852	98855	98857	98860	98862	98865	98867	98870
20.1	98873	98876	98878	98880	98883	98885	98888	98890	98892	98895
20.2	98897	98900	98902	98905	98907	98910	98912	98914	98917	98919
20.3	98922	98924	98927	98929	98931	98934	98936	98938	98941	98943
20.4	98945	98948	98950	98953	98955	98957	98960	98962	98964	98966
20.5	98969	98971	98973	98976	98978	98980	98982	98985	98988	98990
20.6	98992	98994	98996	98998	99001	99003	99005	99007	99009	99012
20.7	99014	99016	99018	99020	99023	99025	99027	99029	99031	99034
20.8	99036	99038	99040	99042	99044	99046	99048	99051	99053	99055
20.9	99057	99059	99061	99063	99065	99067	99069	99071	99073	99075
21.0	99077	99080	99082	99084	99086	99088	99090	99092	99094	99096
21.1	99098	99100	99102	99104	99106	99108	99110	99112	99114	99116
21.2	99118	99120	99122	99124	99126	99128	99130	99132	99134	99136
21.3	99137	99139	99141	99143	99145	99147	99149	99151	99153	99155
21.4	99157	99158	99160	99162	99164	99166	99168	99170	99171	99173
21.5	99175	99177	99179	99181	99182	99184	99186	99188	99190	99192
21.6	99193	99195	99197	99199	99201	99202	99204	99206	99208	99209
21.7	99211	99213	99215	99216	99218	99220	99222	99223	99225	99227
21.8	99229	99230	99232	99234	99235	99237	99239	99241	99242	99244
21.9	99246	99247	99249	99251	99252	99254	99256	99257	99259	99261
22.0	99262	99264	99266	99267	99269	99270	99272	99274	99275	99277
22.1	99279	99280	99282	99283	99285	99286	99288	99290	99291	99293
22.2	99294	99296	99298	99299	99300	99302	99304	99305	99307	99308
22.3	99310	99312	99313	99315	99316	99318	99319	99321	99322	99324
22.4	99325	99327	99328	99330	99331	99333	99334	99336	99338	99339
22.5	99340	99341	99343	99344	99346	99347	99349	99350	99352	99353
22.6	99355	99356	99358	99359	99360	99362	99363	99365	99366	99368
22.7	99369	99370	99372	99373	99374	99376	99377	99379	99380	99381
22.8	99383	99384	99386	99387	99388	99390	99391	99392	99394	99395
22.9	99396	99398	99399	99401	99402	99403	99405	99406	99407	99408
23.0	99410	99411	99412	99414	99415	99416	99418	99419	99420	99421
23.1	99423	99424	99425	99427	99428	99429	99431	99432	99433	99434
23.2	99436	99437	99438	99439	99440	99442	99443	99445	99446	99447
23.3	99448	99449	99450	99452	99453	99454	99455	99456	99458	99459
23.4	99460	99461	99463	99464	99465	99466	99467	99468	99470	99471
23.5	99472	99473	99374	99476	99477	99478	99479	99480	99481	99483
23.6	99484	99485	99486	99487	99488	99490	99491	99492	99493	99494
23.7	99495	99496	99497	99498	99500	99501	99502	99503	99504	99505
23.8	99506	99507	99508	99509	99511	99512	99513	99514	99515	99516
23.9	99517	99518	99519	99520	99521	99522	99524	99525	99526	99527
24.0	99528	99529	99530	99531	99532	99533	99534	99535	99536	99537
24.1	99538	99539	99540	99541	99542	99543	99544	99545	99546	99547
24.2	99548	99549	99550	99551	99552	99553	99554	99555	99556	99557
24.3	99558	99559	99560	99561	99562	99563	99564	99565	99566	99567
24.4	99568	99569	99570	99571	99572	99573	99574	99575	99576	99577
24.5	99578	99579	99580	99581	99581	99582	99583	99584	99585	99586
24.6	99587	99588	99589	99590	99591	99592	99593	99593	99594	99595
24.7	99596	99597	99598	99599	99600	99601	99602	99602	99603	99604
24.8	99605	99606	99607	99608	99609	99609	99610	99611	99612	99613
24.9	99614	99615	99615	99616	99617	99618	99619	99620	99621	99621
25.0	99622	99623	99624	99625	99626	99626	99627	99628	99628	99629
25.1	99630	99631	99632	99633	99634	99635	99636	99636	99637	99638
25.2	99639	99640	99640	99641	99642	99643	99644	99644	99645	99646
25.3	99647	99648	99648	99649	99650	99651	99651	99652	99653	99654
25.4	99655	99655	99656	99657	99658	99659	99659	99660	99661	99661
25.5	99662	99663	99664	99664	99665	99666	99667	99668	99668	99669
25.6	99670	99670	99671	99672	99672	99673	99674	99675	99675	99676
25.7	99677	99678	99678	99679	99680	99681	99681	99682	99683	99683
25.8	99684	99685	99685	99686	99687	99687	99688	99689	99690	99690
25.9	99691	99692	99692	99693	99694	99694	99695	99696	99696	99697
26.0	99698	99699	99699	99700	99700	99701	99702	99703	99703	99704
26.1	99704	99705	99706	99706	99707	99707	99708	99708	99709	99710
26.2	99711	99712	99712	99713	99714	99714	99715	99716	99716	99717
26.3	99717	99718	99719	99719	99720	99720	99721	99722	99722	99723
26.4	99724	99724	99725	99726	99726	99727	99727	99728	99728	99729
26.5	99730	99730	99731	99731	99732	99733	99733	99734	99734	99735
26.6	99736	99736	99737	99738	99738	99739	99739	99740	99740	99741
26.7	99741	99742	99743	99743	99744	99744	99745	99746	99746	99747
26.8	99747	99748	99749	99749	99750	99750	99751	99751	99752	99752
26.9	99753	99753	99754	99755	99755	99756	99756	99757	99757	99758
27.0	99759	99759	99759	99760	99760	99761	99761	99762	99762	99763
27.1	99764	99764	99765	99765	99766	99766	99767	99767	99768	99768
27.2	99769	99769	99770	99770	99771	99771	99772	99772	99773	99773
27.3	99774	99774	99775	99775	99776	99776	99777	99777	99778	99778
27.4	99779	99779	99780	99780	99781	99781	99782	99782	99783	99783
27.5	99784	99784	99785	99785	99786	99786	99787	99787	99788	99788
27.6	99789	99789	99789	99790	99790	99791	99791	99792	99792	99793
27.7	99793	99794	99794	99795	99795	99796	99796	99796	99797	99797
27.8	99798	99798	99799	99799	99800	99800	99800	99801	99801	99802
27.9	99802	99803	99803	99804	99804	99805	98805	98805	99806	99806

TABLE 19.—*Values of* $1-R^x$ *when* $R=0.8$—Continued

x	0	1	2	3	4	5	6	7	8	9
28.0	99807	99807	99807	99808	99808	99809	99809	99810	99810	99810
28.1	99811	99811	99812	99812	99813	99813	99813	99814	99814	99815
28.2	99815	99816	99816	99816	99817	99817	99817	99818	99818	99819
28.3	99819	99820	99820	99820	99821	99821	99821	99822	99822	99823
28.4	99823	99823	99824	99824	99825	99825	99825	99826	99826	99827
28.5	99827	99827	99828	99828	99829	99829	99829	99830	99830	99830
28.6	99831	99831	99832	99832	99832	99833	99833	99833	99834	99834
28.7	99835	99835	99835	99836	99836	99836	99836	99837	99837	99838
28.8	99838	99839	99839	99839	99840	99840	99840	99841	99841	99841
28.9	99842	99842	99842	99843	99843	99844	99844	99844	99845	99845
29.0	99845	99846	99846	99846	99847	99847	99847	99848	99848	99848
29.1	99849	99849	99849	99850	99850	99850	99851	99851	99851	99852
29.2	99852	99852	99853	99853	99853	99854	99854	99854	99855	99855
29.3	99855	99856	99856	99856	99857	99857	99857	99858	99858	99858
29.4	99858	99859	99859	99859	99860	99860	99860	99861	99861	99861
29.5	99862	99862	99862	99862	99863	99863	99863	99864	99864	99864
29.6	99865	99865	99865	99866	99866	99866	99866	99867	99867	99867
29.7	99868	99868	99868	99869	99869	99869	99869	99870	99870	99870
29.8	99871	99871	99871	99871	99872	99872	99872	99873	99873	99873
29.9	99873	99874	99874	99874	99875	99875	99875	99875	99876	99876

LITERATURE CITED

(1) BAULE, B.
1918. ZU MITSCHERLICHS GESETZ DER PHYSIOLOGISCHEN BEZIEHUNGEN. Landw. Jahrb. 51: [363]–385, illus.

(2) MITSCHERLICH, E. A.
1912. ZUM GESETZ VOM MINIMUM. EINE ANTWORT AN TH. PFEIFFER UND SEINE MITARBEITER. Landw. Vers. Sta. 77: [413]–428, illus.

(3) NIKLAS, H., and MILLER, M.
1927. BEITRÄGE ZUR MATHEMATISCHEN FORMULIERUNG DES EXTRÄGGESETZES. Ztschr. Pflanzenernähr., Düngung u. Bodenk. (A) 8: 289–297, illus.

(4) SPILLMAN, W. J.
1921. A PLAN FOR THE CONDUCT OF FERTILIZER EXPERIMENTS. Jour: Amer. Soc. Agron. 13:304–310.

(5) ———
1930. A NEW BASIS FOR FERTILIZER EXPERIMENTS. Science (n. s.) 71: 135–136.

(6) ———
1931. MEASURING ABSORBED PHOSPHATES AND NITROGEN. Science (n. s.) 73: 215–216, illus.

(7) ——— and LANG, E.
1924. THE LAW OF DIMINISHING RETURNS . . . 178 p. Yonkers-on-Hudson.

(8) VERRET, J. A., and KUTSUNAI, Y.
1928. THE YIELD EQUATION AND ITS APPLICATION TO SUGAR CANE AGRICULTURE. Hawaii, Planters' Rec. 32: 61–78, illus.

(9) WHITE, J. W., and HOLBEN, F. J.
1921. SOIL FERTILITY EXPERIMENTS ON DEKALB, VOLUSIA, AND WESTMORELAND SOILS. Penn. Agr. Expt. Sta. Bul. 166, 23 p., illus.

(10) WILLCOX, O. W.
1929. SOME NEW FUNDAMENTALS IN PLANT BIOLOGY, AGRICULTURE AND THE FOOD PROBLEM. Science (n. s.) 69: 609–613.

(11) ———
1930. PRINCIPLES OF AGROBIOLOGY; OR, THE LAWS OF PLANT GROWTH IN RELATION TO CROP PRODUCTION. 96 p., illus. New York.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	HENRY A. WALLACE.
Assistant Secretary	REXFORD G. TUGWELL.
Director of Scientific Work	A. F. WOODS.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Chief.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Division of Farm Management and Costs	C. L. HOLMES, *Principal Agricultural Economist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

TECHNICAL BULLETIN No. 347 FEBRUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

AN ECONOMIC STUDY OF BROOMCORN PRODUCTION [1]

By R. S. WASHBURN, *Assistant Agricultural Economist, Division of Farm Management and Costs, Bureau of Agricultural Economics,* and J. H. MARTIN, *Senior Agronomist, Division of Cereal Crops and Diseases, Bureau of Plant Industry*

The Bureau of Agricultural Economics and Bureau of Plant Industry in Cooperation with the Agricultural Experiment Stations of Illinois and Kansas

CONTENTS

	Page
Introduction	1
Trend of broomcorn production	2
Origin and introduction of broomcorn	2
Shifts of broomcorn growing	3
Quantity of broomcorn produced	4
Price and supply of broomcorn	7
Early prices	7
Recent prices	8
Competition of other products	11
Export demand for American broomcorn	12
Relation of supply of broomcorn to price received	14
Acreage of broomcorn needed to produce an adequate supply	17
Cost of production and returns from broomcorn and competing cash crops	17
Illinois	18
Usual field practice in growing broomcorn and the major competing cash crop	18
Practices that should increase profits	20
Illinois—Continued.	Page
Cost of production	21
Annual broomcorn yields	25
Variation in labor and power requirements	25
Kansas	27
Usual field practice in growing broomcorn and the major competing cash crop	27
Practices that should increase profits	29
Cost of production	29
Oklahoma	32
Usual field practice in growing broomcorn and the major competing cash crop	32
Practices that should increase profits	33
Cost of production	33
Choice of competing cash crops	36
Net returns per acre from broomcorn and competing cash crops	36
Summary	40
Literature cited	41

INTRODUCTION

Broomcorn is unique among our agricultural products in that the brush has practically only one use—the making of brooms. A surplus of broomcorn brush can not be used as food for livestock and is not utilized in other industries. More extensive use of brooms is not stimulated by lower prices, and the export market is decidedly limited. The consumption of broomcorn brush therefore has almost a fixed limit. A short supply of broomcorn brush often results in a very high price, and an oversupply forces the price down to a point that is disastrous to growers.

Broomcorn probably can be grown in nearly every State. Violent fluctuations in production and prices and the heavy cash expense necessary in harvesting and preparing the brush for market frequently make broomcorn one of the most speculative of farm crops.

[1] Acknowledgment is due H. C. M. Case, head of the department of farm organization and management, Illinois Agricultural Experiment Station, and W. E. Grimes, head of the department of agricultural economics, Kansas Agricultural Experiment Station, for cooperation in planning the study in their respective States. Credit is also due Peter Nelson, formerly of the Illinois Agricultural Experiment Station, and R. D. Nichols, formerly of the Kansas Agricultural Experiment Station, for assistance in collecting the basic field data.

151527°—33——1

TREND OF BROOMCORN PRODUCTION

ORIGIN AND INTRODUCTION OF BROOMCORN

The origin of the broomcorn plant has never been determined. It belongs to the group of plants known as sorghums (*Holcus sorghum L., Andropogon sorghum, Brot., Sorghum vulgare Pers.*) but differs from other sorghums in that the branches of the head are produced in the form of a brush. Broomcorn has not been found growing indigenously in Africa nor in Asia, except in Russian Turkestan, although some of the types of sorghums from China and India have brushy heads which can be used for brooms.

Broomcorn probably has been grown in Europe for more than 300 years. Heuze states that it was introduced into Europe in 1596 (*9, v. 1, p. 293*).[2] Possibly it was grown in Europe previous to that date. Apparently the earliest definite report of broomcorn growing in Europe was that of Caspar Bauhin, who states that it was grown in Italy in 1658 (*6, p. 510–516*). At present, broomcorn is grown to a considerable extent in northern Italy, southern France, Hungary, and, to a limited extent, in many other foreign countries.

The introduction of broomcorn into the United States has been credited to Benjamin Franklin according to the following story:

> Doctor Franklin chanced to see an imported corn whisk in the possession of a lady, and whilst examining it as a novelty, he espied a grain of it still attached to the stalk. This he took and planted, and so we at length have got it in abundance among us (*16, v. 2, p. 487*).

The date of introduction is not definitely known.

Another writer has given a somewhat different version of its introduction; he indicates that the plant came from India.

> The seed of broomcorn is a native of the East India, and it is said that Benj. Franklin, while in England, in the year 1725 acquired a seed from a whisp he notice a lady using. He brought it to America, planted and propagated it (*7, p. 8–9*).

This latter origin is doubtful as broomcorn is not now, and apparently never has been, grown in India except experimentally.

According to Thomas Jefferson, broomcorn was grown to some extent in Virginia as early as 1781: "Besides these plants, which are native, our *farms* produce wheat, rye, barley, oats, buckwheat and broomcorn" (*11, p. 42*).

The growing of broomcorn on a commercial scale in this country began in the Connecticut Valley at Hadley, Mass. "According to the Hampshire Gazette, Samuel Hopkins of Hadley was the first to raise broomcorn in this vicinity, about 1778" (*12*).

> Rev. Enoch Hale of Westhampton, in his Diary, May 19, 1785, records that he "sowed broomcorn;" and a few hills may have been planted in several gardens before 1797. Levi Dickinson of Hadley, however, is entitled to the credit of conceiving the plan of raising broomcorn abundantly, and of supplying the country with brooms. * * *
>
> Levi Dickinson, a native of Wethersfield, Conn., obtained a little broomseed, and planted some hills in his garden, on the upper part of the old back-street of Hadley, in 1797. From the seed of this he planted half an acre of broomcorn in 1798,—the first half acre cultivated for brooms in America. In 1799 he planted an acre, and more in succeeding years. * * *
>
> In 1855, assessors of Hadley returned 906 acres of broomcorn, producing 700 lbs. per acre, worth at 10 cents per pound, 63,420 dollars; and 60 bushels of seed

[2] Italic numbers in parentheses refer to Literature Cited, p. 41

per acre, worth at 40 cents per bushel, 21,744 dollars. They returned brooms made in Hadley, 541,120 valued at 118,550 dollars, and 35,000 brushes worth 2,625 dollars (*13, p. 368–369*).

There were 41 places in Hadley making brooms.

SHIFTS OF BROOMCORN GROWING

Shortly after broomcorn had become established in Massachusetts the production began to shift westward. Soon broomcorn became an important crop in the Mohawk Valley of New York. It was grown extensively by Shakers. "The Shaker community at Watervliet, N. Y., are said to have first made brooms for sale in 1798" (*5, p. 11*). Production later moved westward from New York and had assumed considerable importance in the Scioto Valley of Ohio by 1846.

* * * Mr. Eaton, of Chillicothe, who I understand has this season grown the same crop [broomcorn] near Circleville and Chillicothe, in all to the amount of 1000 acres, which has been very nicely prepared, put in bales and pressed, and has already gone forward to be shipped to England, where the owner has workmen employed in manufacturing it into brooms (*10*).

During the late fifties the crop became established in Illinois. One farmer near Rockford, Ill., was reported to have grown 800 acres of broomcorn in 1859 (*2*). John Cofer, of Arcola, Ill., a member of the Illinois Legislature, was reported to have begun the cultivation of broomcorn in east-central Illinois in 1861, where it is still grown extensively. He obtained the seed in Tennessee (*15*).

During the seventies, considerable broomcorn was grown west of the Mississippi. In Kansas, where the crop is still important, production began in 1870.

McPherson County is given credit for having produced the first broomcorn in Kansas. It was in the year 1869 that a Swedish family by the name of Hawkinson came to McPherson County from Illinois. They brought with them quite a lot of broomcorn seed. Knowing that it was a paying sod crop, in the spring of 1870 they planted 80 acres on their claim which they had staked out near Marquette in McPherson County (*3*).

The Smoky Hill and Arkansas Valleys were the chief centers of broomcorn production in Kansas for many years.

The first census reports on broomcorn are for production in the year 1879. Broomcorn was grown to some extent in New York, Ohio, Nebraska, Iowa, Missouri, and California, but even at this early date about 60 per cent of the production was in Illinois and Kansas. The shifts westward were into sections of higher temperatures more favorable for the production of high-quality broomcorn. The following quotation mentions some causes of the shift in production, which occurred more than 75 years ago:

About 1850 the farmers upon the western prairies began the raising of broom corn, exclusively for the brush. It was of larger growth, long and straight, cut while green, and kiln-dried [probably shed cured], and was much better than the brush raised in this [Connecticut] valley, and soon occupied the market. The brooms made from the western brush were of handsome color, the brush having been cut before ripening, they were stronger and a better broom in every way, the outside being covered with the hurls of the brush and no broom made from the native brush could compete with them.

Sixty years has made a great change; the broom-corn industry has left the Connecticut Valley, never to return, and the raising of tobacco and onions seems to have taken the place of broom corn, as the crops relied upon by the farmer for bringing him ready money (*12*).

By 1889 Nebraska was third in importance as a broomcorn State and was exceeded only by Kansas and Illinois. Broomcorn had largely disappeared from New York and Ohio. The crop in Illinois had become more concentrated in the east-central portion of the State and had shifted westward both in Kansas and Nebraska.

Acreage in 1899 showed some increase in Missouri, while acreage in Nebraska had declined. Illinois had become the most important of the broomcorn States, while the increase in acreage in Kansas was only moderate. The crop had made its appearance in Texas, Colorado, and Oklahoma. In the decade 1889–1899 the increase in total broomcorn acreage in the United States was approximately 90 per cent.

By 1909 broomcorn had largely disappeared from Iowa, Missouri, and Nebraska. The crop in Illinois had declined materially, whereas there was a marked increase in acreage in Oklahoma. In 1909 Oklahoma was the leading broomcorn State. Broomcorn had advanced into New Mexico and had moved toward the southwest in Kansas. In Oklahoma the broomcorn acreage of greatest density was in the northwestern part of the State, although the industry became established in the Lindsay district of south-central Oklahoma about this time. The crop in Illinois was confined to the east-central part of the State. During the decade 1899–1909 the increase in total United States broomcorn acreage was approximately 83 per cent.

Broomcorn had become firmly established in the semiarid region of the Southwest by 1919. It had largely disappeared from central Kansas, but had become important in the southwestern part of the State, and was of considerable importance in New Mexico and Colorado. South-central Oklahoma, including the Lindsay district, as well as western Oklahoma were sections of heavy production. A new broomcorn district appeared in the lower Rio Grande Valley in Texas.

By 1929 broomcorn acreage with the exception of that in east-central Illinois was practically all concentrated in the Southwest. Broomcorn acreage in the lower Rio Grande Valley of Texas had largely disappeared, while that of Colorado and New Mexico had increased materially. Southeastern Colorado and northeastern New Mexico were important broomcorn regions. The most recent expansion of broomcorn growing has been in southeastern Colorado and northeastern New Mexico.

As broomcorn is drought resistant, it is adapted to the semiarid conditions of the Plains States, where the choice of cash crops is limited. East-central Illinois and the Lindsay district of Oklahoma are the only humid sections in this country in which broomcorn is grown extensively at present. There the farmers produce a high quality of brush and have a well-established market. Broomcorn has been more profitable for them than have most other crops because of good yields and relatively high prices.

QUANTITY OF BROOMCORN PRODUCED

With the exception of a slight production in Texas and Missouri, broomcorn at present is concentrated in Oklahoma, New Mexico, Colorado, Kansas, and Illinois. The reported production in the United States, according to the census, reached a total of 14,736 short tons in 1879. Census reports by 10-year periods, show an increase to 56,515 short tons in 1919. The first reports on acreage devoted to

broomcorn production are for 1889, in which 93,423 acres were grown as compared with 337,806 acres in 1919. (Table 1.) Starting with 1919, acreage and production are shown in Table 2 as estimated by the United States Department of Agriculture.

TABLE 1.—*Broomcorn acreage and production by States, census years 1879–1929*

State and division	Acreage [1]					Production					
	1889	1899	1909	1919	1929	1879	1889	1899	1909	1919	1929
	Acres	*Acres*	*Acres*	*Acres*	*Acres*	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*
Massachusetts	1	11	2	-------	-------	27	[2]	[2]	1	-------	-------
Connecticut	1	[3]	[3]	[4]	2	2	[2]	[3]	1	[2]	[2]
New York	993	356	2	3	-------	1,463	225	101	1	1	-------
New Jersey	6	11	11	14	-------	14	2	2	3	5	-------
Pennsylvania	57	221	108	946	47	126	18	57	22	147	9
North Atlantic	1,058	599	123	963	49	1,632	245	160	28	153	9
Ohio	1,574	802	170	735	52	752	401	269	46	173	18
Indiana	413	815	323	613	166	215	79	192	77	123	34
Illinois	34,340	95,137	38,452	16,409	21,403	5,822	7,966	30,333	9,655	4,622	5,378
Michigan	11	51	4	27	-------	31	3	12	1	5	-------
Wisconsin	157	64	28	11	-------	101	46	19	7	3	-------
Minnesota	80	149	13	7	12	34	21	38	5	2	2
Iowa	1,108	2,220	156	168	19	585	283	589	38	52	7
Missouri	2,618	10,219	5,339	3,072	987	1,580	526	1,847	887	350	146
North Dakota	-------	3	18	-------	-------	1	-------	1	4	-------	-------
South Dakota	237	239	64	89	11	-------	59	50	18	14	2
Nebraska	16,792	6,627	458	506	159	876	3,257	1,367	79	85	42
Kansas	30,717	34,383	41,064	11,447	49,872	2,842	5,405	5,907	4,384	1,763	6,973
North Central	88,047	150,709	86,089	33,084	72,681	12,839	18,046	40,624	15,201	7,192	12,602
Delaware	14	4	13	9	-------	4	1	2	2	2	-------
Maryland	8	93	19	234	2	20	2	18	10	40	[2]
Virginia	140	1,762	107	360	39	64	22	332	23	58	17
West Virginia	31	82	45	125	1	63	7	16	15	20	[2]
North Carolina	15	67	15	71	17	-------	3	15	3	12	3
South Carolina	54	21	2	2	1	-------	7	6	[2]	1	[2]
Georgia	33	31	22	160	20	-------	4	9	4	26	4
Florida	171	34	-------	-------	-------	-------	98	2	-------	-------	-------
South Atlantic	466	2,094	223	961	80	151	144	400	57	159	24
Kentucky	195	839	342	353	50	-------	46	192	78	59	11
Tennessee	1,439	3,444	1,348	2,247	389	-------	205	508	174	392	57
Alabama	61	152	52	295	28	-------	13	28	9	29	5
Mississippi	41	214	154	309	38	-------	12	72	30	44	9
Arkansas	135	879	332	911	190	-------	27	152	53	141	62
Louisiana	24	107	320	207	47	-------	6	21	46	34	10
Oklahoma	[5] 59	[5] 12,763	216,350	232,733	124,990	-------	[5] 8	[5] 1,783	21,371	35,796	17,938
Texas	596	3,743	9,448	39,748	10,069	-------	158	819	1,184	7,143	1,482
South Central	2,550	22,141	228,346	276,803	135,801	-------	475	3,575	22,945	43,638	19,574
Idaho	13	1	-------	17	11	[2]	2	[2]	-------	4	5
Wyoming	-------	-------	-------	15	-------	-------	-------	-------	-------	3	-------
Colorado	301	1,241	5,631	10,588	64,248	2	30	113	594	2,314	9,200
New Mexico	102	14	4,470	13,113	38,636	-------	12	3	322	2,638	6,156
Arizona	-------	30	14	50	23	[2]	-------	11	3	10	4
Utah	16	19	-------	23	-------	8	7	2	[2]	6	-------
Washington	55	67	183	4	-------	8	11	10	23	1	-------
Oregon	-------	-------	-------	7	-------	-------	-------	-------	-------	1	-------
California	815	1,669	1,023	2,178	114	96	306	573	307	396	24
Far Western	1,302	3,041	11,321	25,995	103,032	114	368	712	1,249	5,373	15,389
United States	93,423	178,584	326,102	337,806	311,643	14,736	19,278	45,471	39,480	56,515	47,598

United States census reports.

[1] Not reported in 1879.
[2] Less than 1 ton.
[3] Not reported.
[4] Less than 1 acre.
[5] Includes Indian Territory.

TABLE 2.—*Broomcorn acreage and production for principal producing States, 1919–1931*

State	1919		1920		1921		1922		1923	
	Acreage	Production	Acreage	Production	Acreage	Production	Acreage	Production	Acreage	Production
	Acres	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*
Illinois	16,000	4,600	20,000	5,000	16,000	4,400	21,000	7,100	40,000	10,200
Missouri	3,000	400	3,000	500	3,000	600	3,000	700	4,000	900
Kansas	11,000	1,800	11,000	2,100	10,000	1,700	16,000	3,100	70,000	13,000
Oklahoma	233,000	35,800	178,000	22,200	146,000	24,100	195,000	20,500	273,000	32,800
Texas	40,000	7,100	33,000	3,800	25,000	3,900	16,000	3,000	51,000	9,300
Colorado	11,000	2,300	7,000	1,500	9,000	1,900	10,000	1,800	48,000	8,800
New Mexico	13,000	2,600	14,000	2,700	13,000	2,600	14,000	2,000	50,000	6,400
Total	327,000	54,600	266,000	37,800	222,000	39,200	275,000	38,200	536,000	81,400

State	1924		1925		1926		1927	
	Acreage	Production	Acreage	Production	Acreage	Production	Acreage	Production
	Acres	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*
Illinois	49,000	11,300	30,000	8,700	40,000	8,900	28,000	5,700
Missouri	4,000	600	3,000	400	2,000	200	1,000	200
Kansas	45,000	6,600	22,000	3,100	33,000	5,100	29,000	5,100
Oklahoma	246,000	45,400	120,000	12,600	169,000	29,600	106,000	19,600
Texas	23,000	4,800	12,000	1,800	16,000	3,100	11,000	1,300
Colorado	19,000	2,500	15,000	1,900	30,000	3,400	35,000	5,800
New Mexico	48,000	6,500	24,000	2,700	29,000	4,400	22,000	2,500
Total	434,000	77,700	226,000	31,200	319,000	54,700	232,000	40,200

State	1928		1929		1930		1931	
	Acreage	Production	Acreage	Production	Acreage	Production	Acreage	Production
	Acres	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*	*Acres*	*Short tons*
Illinois	20,000	4,800	21,000	5,300	28,000	7,800	28,000	8,100
Missouri	1,000	200	1,000	200	1,000	100	1,000	200
Kansas	47,000	9,600	50,000	7,000	60,000	7,400	24,000	3,500
Oklahoma	128,000	23,000	125,000	17,900	164,000	17,100	144,000	18,000
Texas	12,000	1,400	10,000	1,500	10,000	1,400	10,000	1,500
Colorado	53,000	9,500	64,000	9,200	77,000	10,400	45,000	5,600
New Mexico	38,000	5,300	39,000	6,200	51,000	5,600	43,000	7,400
Total	299,000	53,800	310,000	47,300	391,000	49,800	295,000	44,300

Estimates of Division of Crop and Livestock Estimates, U. S. Department of Agriculture.

There is considerable variation in the yield of broomcorn from year to year. (Fig. 1.) Yields in Kansas have been lower in recent years than in the early years of the industry in that State. This lower yield is due, in a large measure, to the fact that the acreage of broomcorn is being more nearly confined to the less productive semiarid sections of the State. During the last two decades the trend in yields in Illinois has been downward. This may be partly the result of soil exhaustion and partly of more careful sorting of the brush at harvest. The tendency during recent years has been to leave unharvested the brush of poor quality and that of lodged crops. The average yield for the United States during the years 1915–1931

was 325 pounds per acre. The range was from 254 pounds (in 1930) to 449 pounds (in 1915). The two factors, varying yield and variation in the acreage planted, have caused wide fluctuations in yearly production.

PRICE AND SUPPLY OF BROOMCORN

EARLY PRICES

Almost from the beginning of production in the United States broomcorn has been subject to considerable price fluctuation, largely as a result of varying supply. In earlier days the growers made the brush into brooms. Soon broomcorn became of greater commercial importance and was marketed directly. Accurate data on the prices paid for broomcorn during the nineteenth century are not available, but newspapers and periodicals occasionally contained statements of prices. In 1825 broomcorn standing in the field was

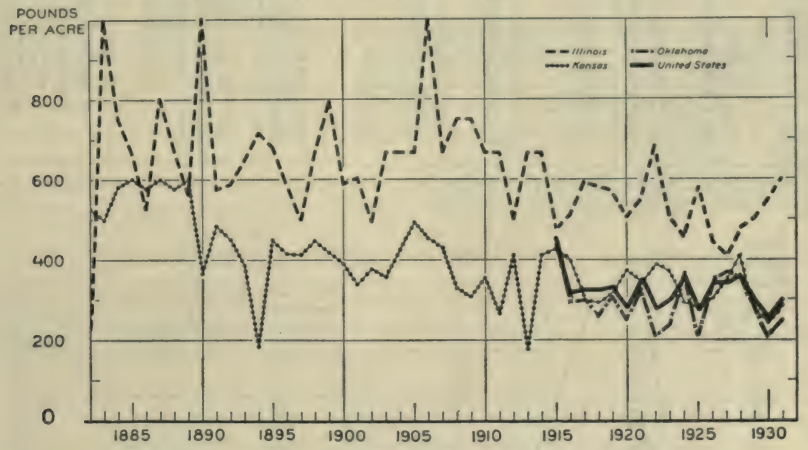


FIGURE 1.—YEARLY YIELD OF BROOMCORN PER ACRE

In general, the yield of broomcorn in recent years has been lower than in the early years of the industry.

valued at $25 to $50 per acre for yields of 300 to 700 pounds of brush per acre. In 1832 the price of broomcorn at Hadley, Mass., was about $100 per ton; in 1835 it advanced to $250 per ton for some of the best-quality brush. During the spring of 1836 the price had advanced to $300 per ton (*1*).

In the years following 1836 the price of broomcorn varied from $60 to $320 per ton, depending upon the quality and the supply. From about 1850 to 1870 the price varied from $100 to $200 per ton in Massachusetts and New York. A large crop in northern Illinois sold for $85 per ton in 1859.

Even in the years previous to 1873 price fluctuations often made broomcorn a very speculative crop.

> The broomcorn interest is a very fluctuating one. The price for the last few years has been about 6 cents for the common kind, and 8 for the other. This last at the close of the [Civil] War brought as high as 18 cents per pound (*8*).

In 1877, the average price of broomcorn in Kansas was reported as $75 per ton. (Table 3.) During the 38 years 1877 to 1914 the

price in Kansas ranged from $32 in 1896 to $138 in 1909. In only 3 of these years, 1909, 1911, and 1913, did the price exceed $90. In 28 of the 38 years the price ranged from $60 to $90 and in 7 years the price was less than $60 per ton. The 10 years from 1890 to 1899 was a period of relatively low prices.

Prices in Illinois, reaching $198 per ton in 1909 (Table 3), were for the most part higher than those in Kansas. From 1877 to 1914, inclusive, the price exceeded $90 per ton during 14 years, and was less than $60 during 7 years. The lowest price was $38 per ton in 1895.

TABLE 3.—*Broomcorn: Average price per ton received by producers in Kansas and Illinois, 1877–1914*

Year	Kansas	Illinois	Year	Kansas	Illinois	Year	Kansas	Illinois	Year	Kansas	Illinois
	Dollars	*Dollars*		*Dollars*	*Dollars*		*Dollars*	*Dollars*		*Dollars*	*Dollars*
1877	75.00	71.20	1887	70.00	69.00	1897	41.46	53.00	1907	66.46	91.00
1878	75.02	49.50	1888	70.00	57.00	1898	44.68	55.00	1908	64.26	89.00
1879	70.00	86.75	1889	70.00	68.00	1899	64.98	171.00	1909	138.27	198.00
1880	69.98	77.40	1890	60.00	64.00	1900	70.18	79.00	1910	81.12	116.00
1881	89.80	128.50	1891	65.00	117.00	1901	80.00	105.00	1911	120.50	177.00
1882	89.98	80.00	1892	65.00	94.00	1902	59.76	79.00	1912	63.38	98.00
1883	69.98	90.00	1893	49.60	57.00	1903	74.36	91.00	1913	99.30	122.00
1884	59.56	72.00	1894	63.90	89.00	1904	61.16	77.00	1914	65.54	87.00
1885	76.12	94.00	1895	40.40	38.00	1905	62.70	86.00			
1886	70.00	78.00	1896	32.40	54.00	1906	61.84	96.00			

Compiled from biennial reports of the Kansas State Board of Agriculture and from the statistical report of the Illinois State Board of Agriculture for Dec. 1, 1914, p. 6.

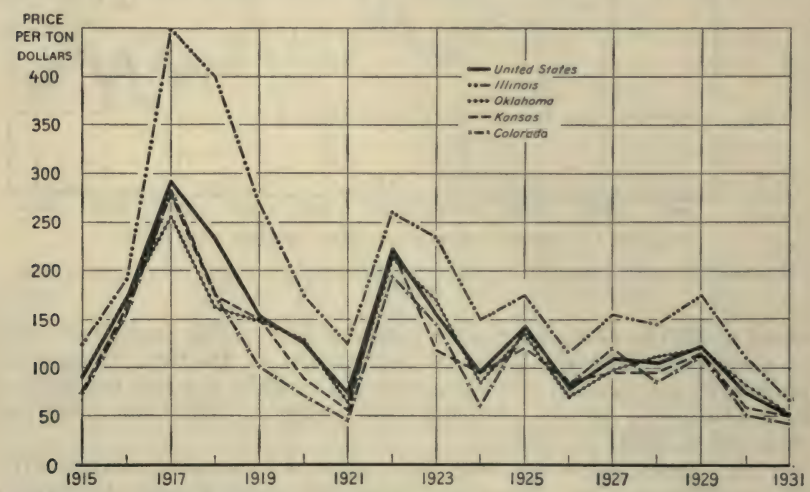


FIGURE 2.—FARM PRICES OF BROOMCORN IN THE UNITED STATES, 1915–1931

The price of broomcorn advanced over the period 1915–1917, but unlike that of most other agricultural commodities it did not advance during the remainder of the World War period

RECENT PRICES

There are no definite daily price quotations on broomcorn such as are available for most other farm commodities. Prices announced by buyers are usually stated in general terms and are not based on a definite grade or quality (*4*). Sales of broomcorn brush by growers at present are usually made on the farm through individual bargaining. Growers who have only a few bales of brush, or those rather remote

from other growers, often have difficulty in getting buyers to come out to look at their broomcorn. For this reason broomcorn for the general market is grown more advantageously in established districts where it can be more readily marketed.

The United States farm price and that in four individual States are shown graphically in Figure 2. For the period 1915–1931 prices for the country as a whole ranged from about $72 per ton in 1921 to about $293 in 1917. Prices in Illinois were considerably higher than those in the other States, particularly Colorado. Since 1915, in all but two years, the Illinois price has been at least $50 higher than the Colorado price. This price differential is mainly due to the better quality of broomcorn in Illinois, but to some extent it is due to the advantage in Illinois of lower freight rates to eastern consuming centers. Broomcorn in Illinois is less subject to drought injury and in most instances is grown, harvested, cured, and stored with more care than in Colorado.

Monthly prices for broomcorn for five States, are shown for the years, 1910 to 1925, in Table 4. These prices are not complete for all months, but they tend to show how prices fluctuated during the different years and from year to year. In many years rather violent changes in the price of broomcorn occurred between June and August during the time that the new crop was coming on the market.

TABLE 4.—*Farm price per ton for broomcorn in Illinois, Kansas, Missouri, Oklahoma, and Texas, by months, 1910–1925* [1]

State and year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Illinois:	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
1910	211	217	217	222	209	154	196	161	168	116	104	103
1911	87	87	86	85	88	79	77	96	126	145	177	158
1912	142	125	125	110	120	108	100	100	95	100	105	84
1913	83	77	77	84	60	92	93	105	140	131	140	113
1914	110	135	120	110	110	105	110	100	-------	100	90	85
1915	82	85	85	95	105	97	120	97	-------	100	125	136
1916	140	130	140	124	125	122	128	-------	130	190	192	220
1917	225	250	300	325	-------	-------	-------	-------	-------	350	450	400
1918	-------	383	425	350	-------	340	-------	-------	468	400	400	250
1919	150	-------	260	200	200	-------	-------	-------	290	330	270	313
1920	288	245	150	260	-------	-------	-------	-------	141	250	175	150
1921	105	140	136	146	110	105	101	103	105	112	125	120
1922	100	120	100	-------	-------	-------	-------	-------	250	200	260	300
1923	-------	-------	-------	375	-------	300	-------	300	-------	255	235	230
1924	210	195	195	195	175	175	150	155	210	200	150	125
1925	130	125	125	120	115	115	140	155	235	235	195	207
Kansas:												
1910	150	153	173	170	190	150	146	103	92	96	82	76
1911	70	62	65	50	55	50	53	60	85	132	130	90
1912	104	75	74	115	75	68	70	80	69	75	76	57
1913	45	57	75	45	39	50	45	55	76	85	93	82
1914	70	79	76	75	71	-------	85	70	70	65	50	50
1915	59	60	73	70	63	67	67	86	66	75	75	95
1916	105	92	95	110	90	-------	110	115	130	175	164	190
1917	174	180	183	220	275	-------	-------	-------	225	250	279	242
1918	225	235	187	183	223	250	200	190	275	210	175	162
1919	131	103	82	120	85	78	86	82	100	120	150	127
1920	123	158	133	104	105	115	124	130	140	112	89	51
1921	56	58	63	50	57	40	40	58	50	66	55	70
1922	78	85	62	76	85	-------	-------	-------	160	198	221	250
1923	260	292	300	331	300	250	300	-------	-------	198	118	124
1924	118	90	90	85	-------	-------	-------	-------	-------	-------	95	95
1925	-------	81	-------	76	47	57	108	130	136	188	179	124
Missouri:												
1910	190	188	200	225	200	175	200	135	109	115	103	100
1911	90	87	78	80	75	75	60	72	78	123	75	110
1912	105	121	92	115	125	105	95	90	90	90	82	127
1913	72	80	72	90	75	75	70	70	80	70	120	95
1914	72	95	90	90	80	90	90	90	-------	88	80	-------
1915	80	74	-------	-------	-------	85	85	90	-------	90	85	90

[1] Monthly prices since 1925 are not available.

TABLE 4.—*Farm price per ton for broomcorn in Illinois, Kansas, Missouri, Oklahoma, and Texas, by months, 1910–1925*—Continued

State and year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Missouri—Con.	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
1916	154											
1917											332	
1918			315						450	400	312	
1919				210	195				220	215		200
1920	205								150	150	145	140
1921	150	125	125	125	125	135	135	125	125	125	125	125
1922	125	125	125	125	125	125	125	125	125	150	225	200
1923	200		237	200	225	270	300	225	200	185	188	200
1924	210	185	190	170	175	170	160	170	175	175	160	150
1925	125		150	00	75	75	80	100	140	235	226	200
Oklahoma:												
1910	156	174	180	181	156	125	144	114	85	76	71	65
1911	65	61	65	59	55	52	71	71	89	113	113	102
1912	90	78	100	95	75	73	84	80	75	60	58	54
1913	40	51	48	55	55	58	50	100	110	102	93	90
1914	98	93	89	89	84	85	85	95	78	60	65	55
1915	65	73	65	67	72	75	75	80	77	87	00	97
1916	97	102	100	90	100	100	98	122	128	164	173	161
1917	175	195	197	200	250	225	192	310	242	253	255	259
1918	260	220	210	200	196	170	250	250	260	248	162	158
1919	176	133	154	145	93	119	130	164	164	160	149	149
1920	160	121	121	144	157	150	113	163	153	124	129	75
1921	55	54	54	50	55	76	80	59	64	64	64	85
1922	61	85	78	75	82	00	83	135	177	199	213	218
1923	230	250	246	208	218	265	200	160	170	180	170	185
1924	100	80	80	85	85	85		180	140	120	85	82
1925	80	78	68	102	81	77	93	147	132	153	166	112
Texas:												
1910	153	187	190	188	198	150	116	115	87	98	86	73
1911	70	74	69	73	72	68	72	68	77	114	100	96
1912	70	89	100	96	85	105	100	88	75	77	76	64
1913	55	50	48	48	55	50	65	67	70	85	81	82
1914	80	76		75	83		83	83	86	60	60	68
1915	60	58	60	62	65	75	65	80	75	78	85	90
1916	96	98	94	85	87	90	88	90	108	125	131	150
1917	160	183	189	199	173	157	244	242	285	255	265	285
1918	270	315	260	220	290	310	274	260	267	270	260	235
1919	190	172	218	160	230	117	135	126	128	128	140	137
1920	130	79	150	147	143	157	134	105	129	90	118	99
1921	90	75	76	79	70	75	70	71	60	68	75	78
1922	72	80			83	82						
1923	190		158	156	111	200	175	125	150	150	150	225
1924		200	200					150	150		100	120
1925			88	125	97	83	78	82	148	96	117	111

Division of Crop and Livestock Estimates.

Table 5 gives the average farm price received for broomcorn on the farms visited during the cost study discussed later. In the majority of instances these prices for standard broomcorn are higher than the average State price as shown in Figure 2. This is to be expected since the broomcorn produced on these selected farms was probably of better quality than that for the State as a whole. In addition, the prices shown in Table 5 for Oklahoma are for standard broomcorn only, while the State averages for Oklahoma and Kansas are for standard and dwarf broomcorn combined. Illinois produces standard broomcorn only.

TABLE 5.—*Average price per ton of broomcorn received by producers on selected farms, 1924–1928*

District and kind of broomcorn	1924	1925	1926	1927	1928	Average
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
East-central Illinois: Standard	196	188	135	147	149	163
Southwestern Kansas:						
Dwarf	95	139	86	97	107	105
Standard	119	118	125	117	111	118
South-central Oklahoma: Standard	212	183	130	165	148	168

COMPETITION OF OTHER PRODUCTS

Broomcorn competes only slightly with any other commodity, whereas a number of products, such as vacuum cleaners and brushes and brooms made of other materials, seriously compete with broomcorn brooms.

The number of broom factories gradually increased from the earliest estimate of 303 for 1849 to a maximum of 1,034 in 1919. Since 1919 there has been a material reduction in the number of broom establishments and a considerable decline in the value of the manufactured product. (Table 6.)

TABLE 6.—*Number of establishments, number of wage earners, and cost and value of the product of the broom industry, in stated years*

Year	Establishments [1]	Average wage earners	Wages paid	Cost of materials	Value of product	Value added by manufacture [2]
	Number	*Number*	*1,000 dollars*	*1,000 dollars*	*1,000 dollars*	*1,000 dollars*
1849	303	1,184	266	529	941	412
1859	228	1,184	288	874	1,428	554
1869 [3]	635	5,206	1,269	3,673	6,622	2,949
1909 [4]	898	5,199	2,363	8,391	14,432	6,041
1914	868	5,642	2,624	7,884	[5] 14,085	6,201
1919	1,034	6,313	5,709	17,365	[5] 30,205	12,840
1921	459	4,302	3,872	10,417	[5] 18,188	7,771
1923	444	4,730	4,482	14,933	26,262	11,329
1925	421	4,725	4,654	11,213	21,714	10,501
1927	397	4,450	4,275	9,176	18,445	9,269
1929	404	4,542	4,169	9,648	19,166	9,518

[1] U. S. Census of Manufactures, 1921, 1927, and 1929. The establishments classified in the broom industry are engaged primarily in the manufacture of brooms, whisk brooms, etc., made from broomcorn, but some are made of bristles, and others, such as street or push brooms, are made of heavier material.

[2] Value of product minus cost of materials.

[3] Monetary items in depreciated currency worth in gold approximately 80 per cent of its nominal value.

[4] The census for 1909 and subsequent years does not include a considerable number of small establishments that reported products valued at less than $5,000.

[5] In addition, the manufacture of brooms valued as follows was reported by establishments in other industries: For 1914, $167,466; for 1919, $228,705; for 1921, $220,697.

Although many of the small and the less efficient broom factories have ceased operation, nearly as many brooms are made now as in previous years. Much of the decline in the total annual value of brooms manufactured is the result of lower prices.

The decline, or lack of expansion, in the broom industry is primarily due to the increasing competition of other products. Perhaps the chief competitor is the vacuum cleaner. According to the census of manufacture the value of electric vacuum cleaners manufactured in 1914 amounted, in round numbers, to $2,000,000 and in 1929 to $34,000,000, or an increase for the period of approximately sixteen times the value of the product in 1914. (Table 7.)

TABLE 7.—*Number of electric vacuum cleaners manufactured and value of product in the United States, in stated years*

Year	Number manufactured	Value of product [1]	Year	Number manufactured	Value of product [1]
	Thousands	*1,000 dollars*		*Thousands*	*1,000 dollars*
1914	2,059		1925	1,108	39,971
1919	[2] 977	[2] 21,842	1927	1,128	36,222
1921	740	19,753	1929	[3] 1,382	[3] 34,480
1923	1,241	35,981			

U. S. Census of Manufactures, 1921, 1927, and 1929.

[1] Does not include establishments that reported products valued at less than $5,000.

[2] Figures not strictly comparable with other years because of inclusion of vibrators, clippers, and cutters.

[3] In addition, vacuum cleaners to the value of $627,545 were made by manufacturers who did not report the number.

Another contributing factor in the decline of the broom industry is the increasing importance of that portion of the brush industry having to do with the manufacture of clothes, bonnet, and hat brushes and brushes for household purposes. A majority of these compete directly with whisk brooms made from broomcorn. They are made mostly from fibers and bristles imported from the Tropics or from Asia. The value of brushes of this type manufactured in 1927 amounted to approximately $11,000,000. The brush industry as a whole had so expanded, that the value of the product in 1929 amounted to $46,000,000 (Table 8) in comparison with a value for the broom industry of $19,000,000. Carpet sweepers, dust mops, and hair push brooms also reduce the consumption of broomcorn brooms. Because of the keen competition of other products the outlook for any material expansion of the broom industry does not appear very favorable. Broomcorn brooms are still found in nearly all homes, hotels, and offices, but are used less than in former years and consequently are not worn out so quickly. Despite the increase in population in the United States, the consumption of broomcorn appears to have declined slightly since about 1924. Broomcorn brooms, however, will be used for many more years because they are more satisfactory for many purposes than is any other product yet devised.

TABLE 8.—*Number of establishments, number of wage earners, and cost and value of the product of the brush industry, in stated years*

Year	Establishments [1]	Average wage earners	Wages paid	Cost of materials	Value of product	Value added by manufacture [2]
	Number	*Number*	*1,000 dollars*	*1,000 dollars*	*1,000 dollars*	*1,000 dollars*
1849	146	2,405	533	638	1,574	936
1859	121	2,378	594	994	2,097	1,103
1869 [3]	157	2,425	691	1,313	2,695	1,382
1909 [4]	384	6,954	3,041	7,187	14,694	7,507
1914	359	7,213	3,461	9,327	[5] 17,894	8,567
1919	379	7,968	7,113	19,598	[5] 39,006	19,408
1921	277	6,460	6,415	18,665	35,545	16,880
1923	306	8,719	9,208	25,570	50,511	24,942
1925	302	7,836	8,452	22,021	45,824	23,803
1927	302	7,673	8,244	22,553	47,844	25,291
1929	303	7,261	7,963	21,688	45,549	23,861

U. S. Census of Manufactures, 1921, 1927, and 1929.

[1] The establishments classified in the brush industry are engaged primarily in the manufacture of brushes other than rubber, such as tooth, toilet, paint, varnish, clothes, bonnet and hat brushes, household, and industrial brushes.

[2] Value of product minus cost of materials.

[3] Monetary items in depreciated currency worth in gold approximately 80 per cent of its nominal value.

[4] The census for 1909 and subsequent years does not include establishments that reported products valued at less than $5,000.

[5] In addition, the manufacture of brushes valued as follows was reported by establishments in other industries: For 1914, $946,283; for 1919, $274,762; for 1921, $491,227.

EXPORT DEMAND FOR AMERICAN BROOMCORN

Except in Canada and Cuba there does not seem to be much prospect of expanding the foreign demand for American broomcorn. Among the factors affecting the demand is the wide use of other broom and brush-making material, competition of broomcorn from other nearer sources of supply, tariff barriers, and in many cases a deep-rooted prejudice against the American style of broom.

The United States exports of broomcorn for the 6-year period 1925–1930 have averaged about 4,400 long tons annually. (Table 9.) Canada, using about 3,000 long tons annually, provides the most important market for American broomcorn. Canada produces very

little broomcorn, and unless some other fiber is adopted as a substitute, will probably continue to be dependent on the United States for the limited quantity used in the manufacture of broomcorn products in that country. Cuba, taking an average of about 850 long tons annually, is the second largest user of American broomcorn. Exports to all other foreign countries, including Mexico and Panama, usually amount to less than 500 long tons annually.

TABLE 9.—*Exports of broomcorn from the United States, by countries, 1925–1930*

Country to which exported	Calendar year					
	1925	1926	1927	1928	1929	1930
	Short tons	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*
Canada	4,083	3,343	3,405	3,798	2,806	3,860
Cuba	950	821	822	1,021	1,183	934
Mexico	353	214	174	96	56	68
Panama	31	58	59	34	102	30
Other countries	84	136	74	105	749	39
Total	5,501	4,572	4,534	5,054	4,896	4,931

Compiled from reports of Foreign Commerce and Navigation of the United States.

Italy, Hungary, and France are the principal foreign countries in which broomcorn is produced in commercial quantities; Italy, Hungary, and the United States are the only countries producing broomcorn in excess of domestic needs. Practically all of the domestic crop in France is consumed in that country and is supplemented by imports. But there is no market in France for American broomcorn or brooms as the Italian and Hungarian product is cheaper.

In addition to broomcorn, limited quantities of brooms are exported, principally to Honduras, Panama, the Dutch West Indies, Colombia, and the Philippine Islands. Such exports in 1930 amounted to 17,167 dozens, valued at $81,384. (Table 10.) It would require less than 250 tons of broomcorn for the manufacture of this number of brooms.

TABLE 10.—*Exports of brooms from the United States, by countries, calendar years, 1928–1930*

Country to which exported	1928		1929		1930	
	Quantity	Value	Quantity	Value	Quantity	Value
	Dozen	*Dollars*	*Dozen*	*Dollars*	*Dozen*	*Dollars*
United Kingdom	202	863	242	1,081	159	701
Canada	826	5,164	506	3,546	600	3,418
Honduras	2,584	9,414	3,259	11,361	3,153	10,732
Panama	1,638	8,613	2,252	10,222	2,103	10,034
Mexico	428	3,333	556	4,078	549	3,659
Cuba	902	5,659	986	7,141	429	3,375
Dominican Republic	742	4,782	229	1,564	328	1,840
Dutch West Indies	897	4,250	1,047	4,517	907	4,147
British Honduras	494	1,611	660	2,071	801	2,494
Costa Rica	226	1,394	274	1,013	107	559
Guatemala	596	2,826	615	2,708	463	2,119
Nicaragua	476	1,857	396	1,814	322	1,306
Other British West Indies	214	1,212	240	1,269	211	1,051
Haiti	118	1,282	112	460	76	490
Bolivia	402	1,790	1,009	5,082	795	4,105
Chile	134	1,299	431	2,871	333	2,234
Colombia	1,405	6,961	1,372	6,317	1,046	5,354
Peru	127	1,213	433	2,229	470	2,580
Venezuela	362	2,310	438	2,950	607	3,371
China	322	1,424	186	746	81	296
Philippine Islands	1,074	4,556	1,593	6,291	2,144	8,899
French Oceania	443	1,565	433	1,489	399	1,441
Union of South Africa	496	6,428	55	627	179	1,985
Other countries	834	4,779	1,381	7,865	905	5,194
Total	15,942	84,585	18,705	89,312	17,167	81,384

Foreign Commerce and Navigation of the United States and official records of the Bureau of Foreign and Domestic Commerce.

RELATION OF SUPPLY OF BROOMCORN TO PRICE RECEIVED

Broomcorn prices are not controlled by world conditions of supply and demand. The United States is by far the principal producer of broomcorn, exports are fairly constant, and imports are of little importance as they have seldom exceeded 100 short tons per year during recent years. For these reasons the supply within the United States is the controlling factor determining the price received by American producers. Broomcorn supply and distribution for the last few years are shown in Table 11.

TABLE 11.—*Supply and distribution of broomcorn in the United States, 1923–24 to 1931–32*

Crop year (June 1 to May 31)	Supply						Distribution			
	Stocks on hand June 1			Production	Imports	Total	Export	Domestic use	Stocks on hand May 31	Total
	Manufacturers	Dealers [1]	On farms							
	Short tons	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*	*Short tons*
1923–24	8,018	2,421	[2]	81,400	550	92,389	5,099	50,499	36,791	92,389
1924–25	15,169	15,489	6,133	77,700	136	114,627	5,580	[3] 57,020	52,027	114,627
1925–26	20,960	25,043	6,024	31,200	[2]	83,227	4,688	49,367	29,172	83,227
1926–27	16,201	9,706	3,265	54,700	[2]	83,872	4,701	46,791	32,380	83,872
1927–28	18,173	11,498	2,709	40,200	193	72,773	4,367	42,518	25,888	72,773
1928–29	18,744	5,938	1,206	53,800	[2]	79,688	4,931	46,848	27,909	79,688
1929–30	19,591	7,495	823	47,300	[2]	75,209	4,985	47,534	22,690	75,209
1930–31	14,980	6,667	1,043	49,800	[2]	72,490	4,557	43,953	23,980	72,490
1931–32	17,088	4,566	2,326	[4] 44,300	[2]	68,280	3.713	39,367	25,200	68,280

Division of Hay, Feed, and Seeds.

[1] Storage stocks reported by dealers include manufacturers' stocks held by dealers at country shipping point.

[2] Less than 100 tons. Not counted in total supply.

[3] Includes waste and broomcorn destroyed by warehouse fire.

[4] Nov. 1 estimate.

Figure 3 shows the relation of the total United States available supply to the price received for broomcorn. Since the uses of broomcorn are almost entirely limited to the making of brooms and since the demand for domestic use is satisfied at about 45,500 short tons, a supply greater or less than these requirements, plus an annual export demand of approximately 4,500 short tons, results in a decided change in the price received.

The change in price from the preceding year, that has occurred over the period 1923–1931, as a result of a production above or below the average domestic requirement in recent years of about 45,500 short tons, plus exports of about 4,500 short tons, or a total of about 50,000 short tons is illustrated in Figure 4. In this chart the change in adjusted price from the preceding year is represented in the vertical scale, and the production of broomcorn above or below a 50,000 short-ton requirement is represented in the horizontal scale. The price changes and production data have been plotted on the chart for each crop year, and the heavy diagonal line of average relationship has been drawn in free hand. For most of these years there is a rather marked correlation between the production above or below the 50,000 short-ton requirement and the change in price. In 1926 and 1930 the quality of much of the broomcorn was poor.

The line of average relationship shows that in years of a production of approximately 10,000 short tons below average requirements broomcorn has sold at a price about $15 per ton higher than during the pre-

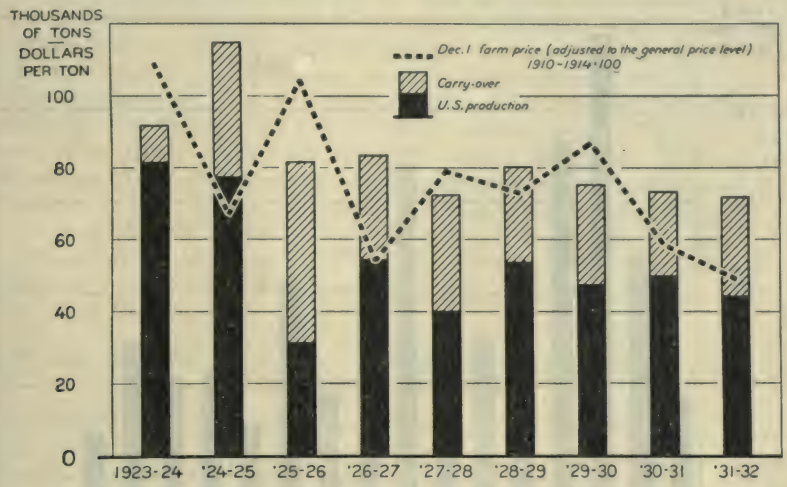


FIGURE 3.—UNITED STATES SUPPLY AND ADJUSTED FARM PRICE OF BROOMCORN, 1923–24 TO 1931-32

Over the period 1923 to 1931, both total supply and price have shown a slight downward trend.

vious year. Likewise the price of brush has been about $15 per ton lower than that for the previous year for a production of 10,000 short tons above average requirements. This relationship may not hold

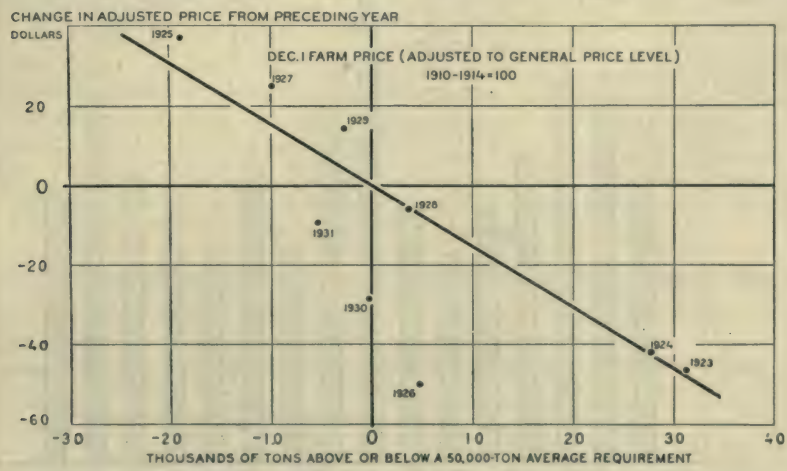


FIGURE 4.—BROOMCORN PRODUCTION ABOVE OR BELOW THE AVERAGE REQUIREMENT OF 50,000 SHORT TONS AND THE CHANGE IN ADJUSTED PRICE FROM THE PRECEDING YEAR, 1923–1931

For these years the heavy diagonal line indicates that low prices have accompanied above-average production and vice versa.

with exactness in the future, but its general nature is evident and serves to point out the quick response in prices downward as a result of overproduction and the danger of unprofitable returns to broom-

corn growers whenever supply exceeds average requirements. In years when the quality of the brush is exceptionally good or poor, greater or smaller price changes may be expected than the normal

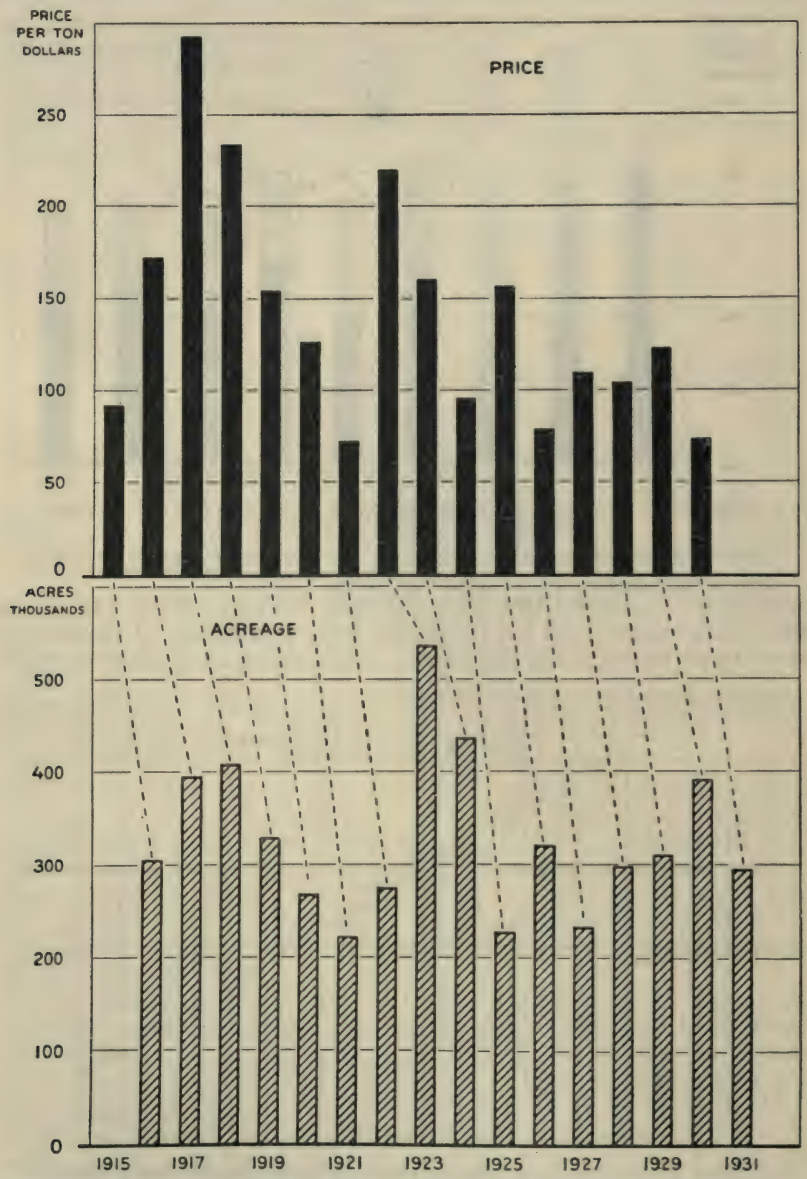


FIGURE 5.—UNITED STATES FARM PRICE OF BROOMCORN, 1915–1930, AND ACREAGE, 1916–1930

Broomcorn acreage is influenced, from year to year, largely by the price received the preceding year.

relationship would indicate. Also these reactions to price may undergo a degree of change owing to changes in the general price level, as will happen in the case of other commodities.

ACREAGE OF BROOMCORN NEEDED TO PRODUCE AN ADEQUATE SUPPLY

Allowing for a yield of approximately 314 pounds of broomcorn per acre, the average yield for the five years, 1927–1931, about 320,000 acres are required for domestic use and exports, or a total of 50,000 short tons, in recent years. (Table 11.) Allowance, of course, must be made for variation in yields, but an acreage greater than that is likely to result in unfavorable prices to broomcorn growers.

The acreage planted to broomcorn in a given year is influenced largely by the prices received for the previous crop. Figure 5 shows that during the 17-year period, 1915 to 1931, in all years except two, a decrease in price over that of the previous year was followed by a reduction in the acreage of broomcorn planted the following year and an increase in price was followed by an increase in acreage. The exceptions were 1921 and 1928. The tendency to increase acreage following a year of increasing prices works to the material disadvantage of the broomcorn grower.

COST OF PRODUCTION AND RETURNS FROM BROOMCORN AND COMPETING CASH CROPS

To obtain data relative to methods and costs of producing broomcorn, growers were interviewed in three representative broomcorn districts and detailed facts were obtained concerning methods and costs of producing broomcorn in 1928. In addition, enough information was obtained to afford a basis for comparison of the net returns from broomcorn and the major competing cash crop as determined by natural conditions and different price relationships in each of the important districts. The districts surveyed were: (1) Coles and Cumberland Counties in east-central Illinois; (2) Seward and Stevens Counties in southwestern Kansas; and (3) Garvin and McClain Counties in south-central Oklahoma. Coles and Cumberland are the principal broomcorn-producing counties in Illinois. Seward and Stevens Counties are typical broomcorn-producing sections of southwestern Kansas, the Oklahoma panhandle, southeastern Colorado, and northeastern New Mexico. Garvin and McClain Counties are representative of broomcorn production in south-central Oklahoma.

The study is based on 189 farm records. The number of farms studied in each district, together with the average acreage of the various crops grown on these farms, is shown in Table 12.

TABLE 12.—*Distribution of crop acreage on selected farms, by State and district, 1928*

State and district	Farms studied	Crop acreage per farm									
		Broomcorn	Corn	Oats	Wheat	Barley	Cotton	Grain sorghum	Hay	Miscellaneous	Total
	Number	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*
Illinois, east central	100	36	84	32	2	1	----	----	10	1	166
Kansas, southwestern	53	68	25	----	63	----	----	135	11	1	303
Oklahoma, south central	36	48	21	9	4	----	45	4	12	....	143

In all three districts the growing of cash crops, rather than mixed farming or the production of livestock, represents the prevailing farming system. At least one important cash crop in addition to broomcorn was grown on every farm visited. The major competing cash crop in east-central Illinois is corn (maize); in southwestern Kansas it is grain sorghums, mainly milo, and in south-central Oklahoma it is cotton. Broomcorn is not the leading cash crop in any district, although in south-central Oklahoma the acreage of broomcorn in usually slightly greater than that of cotton on the farms on which broomcorn is grown. There is considerable variation from year to year in the acreage of broomcorn grown in each district, owing largely to the competition between broomcorn and the major competing cash crop. Broomcorn competes directly with corn, sorghums, and cotton for labor previous to harvest and is a crop of especial financial risk whenever production exceeds the normal requirement.

Most of the broomcorn farmers keep only enough cows to supply milk for home use. The Illinois farmers had an average of 3 brood sows, the Kansas farmers had 1, and the Oklahoma farmers had 2 per farm. Sheep are not common in any of the districts. About 100 chickens are kept on most of the farms in each of the three districts. In addition, on a few farms turkeys, guinea fowls, and geese are found.

In the following sections, cost of production and the returns from broomcorn and the major competing cash crops are presented by districts.

ILLINOIS

East-central Illinois has been an important broomcorn district for many years. Standard broomcorn only is grown. The average annual precipitation is about 38 inches. As rains frequently occur during the harvesting period, all of the brush is cured in sheds. Most of the broomcorn is grown on dark prairie soils. It is usually grown in a rotation following corn, wheat, or oats, except where it follows broomcorn. Winter wheat occasionally winter kills, and when this occurs part of the land may be planted to broomcorn.

USUAL FIELD PRACTICE IN GROWING BROOMCORN AND THE MAJOR COMPETING CASH CROP

In general the methods of growing broomcorn are nearly identical with those of growing corn. On the other hand, the methods of harvesting and curing broomcorn are peculiar to that crop.

The initial soil preparation in seed-bed preparation for broomcorn consists mainly of plowing. Ninety-three of one hundred broomcorn growers plowed their land, and seven double disked twice without plowing. Most of the land that was not plowed for broomcorn had been plowed in the fall previous to seeding to wheat which was subsequently winterkilled. Most of the plowing in Illinois is done with 2-bottom tractor plows. The plowed land is usually disked and harrowed before planting. The growers plant broomcorn with ordinary 2-row corn planters equipped with special broomcorn-planting plates. Broomcorn requires replanting more frequently than does corn because the seeds and young plants are more tender and because uniform stands are more necessary. Corn is usually given one more cultivation than broomcorn. In other respects the preharvest work

on corn is almost identical with that on broomcorn. The usual rate of planting broomcorn is 1 bushel to 20 acres; that for corn is 1 bushel to 8 acres. Most of the planting is done in May and the remainder in April or June.

The methods of harvesting broomcorn depend upon the height of the stalks and the local custom. Broomcorn harvest usually begins in August and continues through September. All of the crop is tabled and cut. Tabling is done by men who walk backward between two rows, break the stalks over about waist-high, and overlap the upper portion of the stalks at an angle across the rows to form a flat so-called table with two rows. The heads of one row then extend horizontally out beyond the edge of the adjoining row in a convenient position for cutting. (Fig. 6.) The stem is cut at an angle with a special knife at

FIGURE 6.—Field of broomcorn, partly tabled, showing the harvested heads lying in piles on the table

a point 6 to 8 inches from the base of the brush. The brush is bunched or piled in convenient armfuls on alternate tables. This operation of tabling and cutting broomcorn alone requires nearly twice the total man labor involved in harvesting, cribbing, and delivering to the local elevator the corn produced on an acre of land, if, as is usual, the corn is husked from the standing stalks and delivered to the elevator in double box wagons.

The brush is hauled on special dump racks about 12 to 16 feet long. (Fig. 7.) The wagons straddle the empty table and are loaded by two men working on opposite sides. The bunches are laid in two tiers on the rack with the seed ends of the brush outside. The brush is hauled to the broomcorn seeder where the rack, known as a dump or float, is tipped down and then pulled out from under the load, which slips to the ground.

The process of removing the seed from the brush is known as threshing, seeding, or scraping. The threshing is done before the brush is cured. Most of the broomcorn is threshed with large power seeders (fig. 8) that require crews of 10 to 30 men.

Curing sheds are usually built in the form of stalls or bins, 7½ feet wide and any desired length. The stalls in most of the sheds run lengthwise of the shed. A stall 7½ feet wide, 24 feet long, and 10 feet high holds 1½ tons of cured brush piled 3 inches deep on the slats. The slats are 1 by 2 inch strips laid across the cleats, which are 1 by 4 inch boards spaced 2 inches apart.

The brush is taken directly from the seeder to the slats in the shed. Seeding before curing results in a better quality of brush than seeding done after curing because fewer of the fine fibers are removed. The large amount of labor necessary in seeding broomcorn is due mainly to the care devoted to keeping the brush straight, even, and untangled. Several men are occupied in carrying the brush in small armfuls to the feeding table and several in carrying it from the machine to the

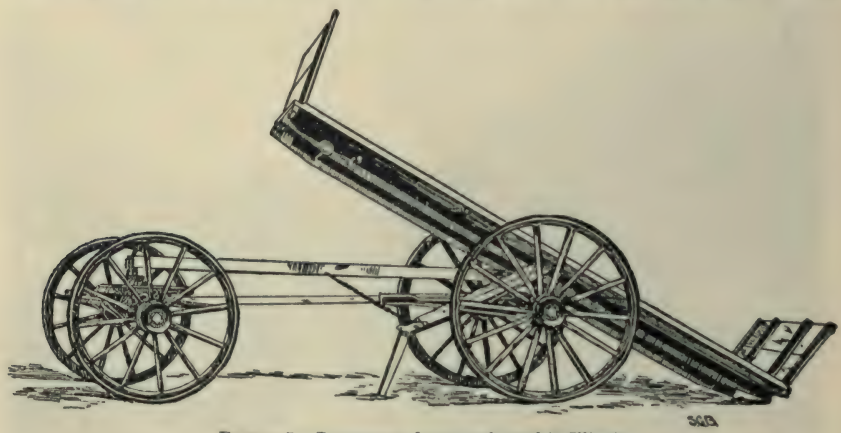


FIGURE 7.—Broomcorn dump rack used in Illinois

shed and placing it on the slats. The remaining men sort and untangle the brush and even up the ends to facilitate uniform threshing. A tractor is the usual source of power to operate the seeder; but in some instances the seeder is mounted on motor trucks, and the power is taken from the truck motor.

Broomcorn is usually baled immediately after it is cured or as soon thereafter as possible. Curing usually requires 10 to 14 days. About one-half of the crop is "bulked down" before being baled. Bulking down consists in removing the brush from the slats and piling it on the floor of the shed. This prevents appreciable shrinkage from further drying, reduces the number of men necessary for baling, and makes room for additional brush. Each bale is tied with five strands of Nos. 9, 10, or 11 size wire. The bales vary in weight from 250 to 400 pounds, averaging about 333 pounds.

PRACTICES THAT SHOULD INCREASE PROFITS

Broomcorn has been grown for many years and good practices have been generally adopted. There appears to be little opportunity for improving on the methods followed by the better growers.

Some saving in labor would probably result from the more general use of tractor plows and disks and of 2-row cultivators. (Table 15.) Baling brush directly from the slats without bulking down will reduce the total man-labor requirement by about 15 hours per ton and will save some cash expense when hired labor is employed for bulking. Prompt baling will eliminate the necessity for bulking to avoid shrinkage and still make shed space available for more brush.

COST OF PRODUCTION

Producing broomcorn on an extensive scale requires more capital than does the major competing cash crop in each district. Some special broomcorn equipment is necessary, and a relatively large cash outlay for labor to harvest the crop is essential to successful production of broomcorn.

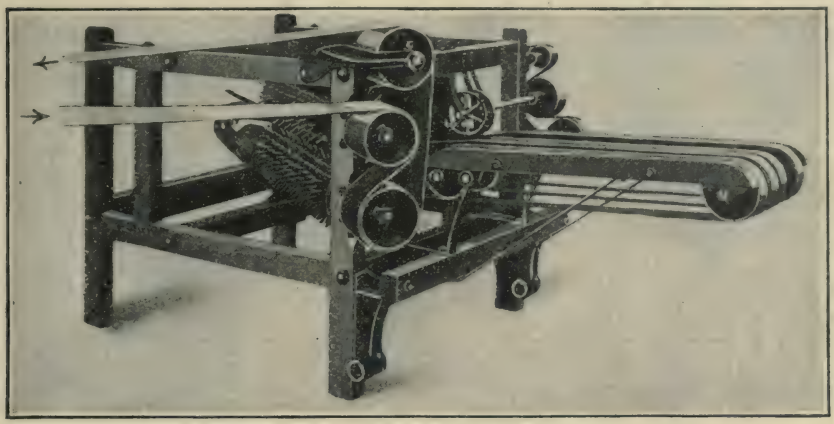


FIGURE 8.—Side view of a self-feed broomcorn seeder

The principal items entering into the cost of broomcorn production are man labor, horse and tractor work, seed, taxes, use of equipment, and land. The cost of producing broomcorn is summarized in Table 13. These cost estimates are based on the usual field practice and cost rates as in 1928.

Under the usual field practice of using tractors for plowing and disking, with a yield of 600 pounds of brush per acre, farmers produce an acre of broomcorn with about 42 hours of man labor, 17½ hours of horse work, and 2½ hours of tractor work. These requirements amount to 141 hours of man labor, 59 hours of horse work, and 8 hours of tractor work per ton.

Materials such as seed and baling wire are a relatively small item of expense, amounting to 48 cents per acre, or $1.60 per ton of brush.

Other costs, including taxes, fire insurance on the brush, use of machinery, use of broomcorn shed, losses due to abandoned acreage, replanting, and overhead expenses, amount to about $7.50 per acre.

In 1928 broomcorn land in east-central Illinois was valued at about $150 per acre. Interest charges are frequently considered a part of production costs, and when figured at 5 per cent of this land valuation, amount to $7.50 per acre.

TABLE 13.—*Cost of producing standard broomcorn brush, according to the usual field practice and at cost rates prevailing in 1928* [1] *in east-central Illinois*

Item	Size of crew			Rate of work per day	Times operation is performed	Quantity and cost [2]							
						Per acre				Per ton			
	Men	Horses	Tractors			Man-hours	Horse-hours	Tractor-hours	Cost	Man-hours	Horse-hours	Tractor-hours	Cost
Labor and power:													
Preharvest—				*Acres*									
Plow (2-bottom 14-inch)	1		1	7	1	1.4		1.4	$1.50	4.7		4.7	$5.03
Disk (tandem 8-foot)	1		1	20	2	1.0		1.0	1.07	3.3		3.3	3.53
Harrow (3-section 15-foot)	1	4		30	1	.3	1.2		.22	1.0	4.0		.74
Plant (2-row corn planter)	1	2		20	1	.5	1.0		.24	1.7	3.4		.82
Cultivate (1-row riding)	1	2		7	3	4.3	8.6		2.06	14.3	28.6		6.86
Miscellaneous						1.0	.8		.32	3.3	2.4		1.04
Harvest [3]—													
Table and cut (contract) [4]	24			13	1	18.5			6.80	61.7			22.67
Haul to shed	4	4		11	1	3.6	3.6		1.91	12.0	12.0		6.36
Seed and shed—				*Tons*									
Farm crew	25			18.5	1	4.1			1.64	13.7			5.48
Contract [5] (power seeder)	1					.2			1.00	.7			3.33
Bulk down	3			4	1	2.2			.88	7.3			2.92
Bale—													
Farm crew	9			11	1	2.4	.6		.96	8.0	2.0		3.20
Contract [6]	1	2				.3			.36	1.0			1.20
Haul to market (5 miles with wagon)	1	2		3	1	1.0	2.0		.66	3.3	6.6		2.18
Supervision [7]						1.0			1.00	3.3			3.33
Miscellaneous						.5			.20	1.6			.64
Total						42.3	17.8	2.4	20.82	140.9	59.0	8.0	69.33
Materials:													
Seed, 2½ pounds, at 12 cents per pound									.30				1.00
Baling wire									.18				.60
Total									.48				1.60
Other costs:													
Taxes									1.75				5.83
Fire insurance on brush (2 months)									.45				1.50
Use of machinery									.65				2.17
Use of broomcorn shed									1.64				5.47

Loss on abandoned acreage									.49				1.63
Overhead									2.54				8.47
Total									7.52				25.07
Total exclusive of interest									28.82				96.00
Interest on land, at 5 per cent									7.50				25.00
Total cost, including interest									36.32				121.00

[1] Man labor previous to harvest charged at 22 cents per hour, harvest labor except that done on a contract basis, at 40 cents per hour, horse work at 13 cents per hour, and tractor work at 85 cents per hour.
[2] Based on a yield of 600 pounds per acre.
[3] All work done on a contract basis has been reduced to hours of man labor and horse and tractor work, but is charged at the contract rate for such work.
[4] Charged at the custom rate of $5 per acre plus value of board.
[5] Charged at the custom rate of $1 per acre.
[6] Charged at the custom rate of 20 cents per bale of 333 pounds.
[7] Charged at the custom rate of $1 per acre.

Including interest on land, the total cost in 1928 amounted to $36 per acre. The cost per ton amounted to about $121 on the basis of a yield of 600 pounds per acre. This yield is somewhat higher than the average for the State but is representative of average yields obtained on the better broomcorn soils in Illinois. Excluding interest charges, the cost per acre amounted to about $29.

The cost analysis just presented considered all legitimate items of cost, including the labor of the farmer and members of his family. It should be kept in mind, however, that many of the cost items are noncash. A division of the cost of broomcorn production into cash and noncash items may explain why some men are able to continue in the business of broomcorn growing for a time when producing at a total cost that is higher than the market price. In many instances much of the labor is performed by the farmer and his family, and where his land, machinery, and work stock are free of indebtedness a large part of the expense that correctly enters into cost of production is not an actual cash outlay. Growers who had no indebtedness, hired no preharvest labor, hired no field boss, exchanged labor for baling, and hauled the crop to market themselves could produce broomcorn in 1928 for an actual cash outlay of approximately $19 per acre or 53 per cent of the total cost of production. (Table 14.) This applies more particularly to farmers with medium acreages who did not need to hire preharvest labor.

TABLE 14.—*Estimated cash and noncash cost per acre of producing broomcorn in east-central Illinois, 1928* [1]

Item	Cash cost per acre		Noncash cost per acre	
	Dollars	*Per cent*	*Dollars*	*Per cent*
Preharvest:				
Man labor			1.87	5.1
Horse work			1.51	4.2
Tractor work	2.03	5.6		
Harvest:				
Table and cut	6.80	18.7		
Haul to shed [2]	1.44	4.0	.47	1.3
Seed and shed	2.64	7.3		
Bulk down	.88	2.4		
Bale [3]	.36	1.0	.96	2.6
Haul to market			.66	1.8
Supervision			1.00	2.8
Miscellaneous			.20	.6
Materials:				
Seed	.30	.8		
Baling wire	.18	.5		
Other costs:				
Taxes	1.75	4.8		
Fire insurance on brush	.45	1.2		
Use of machinery	.43	1.2	.22	.6
Use of broomcorn shed	.82	2.3	.82	2.3
Loss on abandoned acreage			.49	1.3
Overhead	1.27	3.5	1.27	3.5
Interest on land			7.50	20.6
Total	19.35	53.3	16.97	46.7

[1] On the basis of the grower owning his land and equipment free from indebtedness and hiring no help previous to harvest. If 1 man is hired previous to harvest, the cash cost of preharvest labor would be approximately 93 cents per acre.

[2] On the basis of a cash expense for all of the man labor.

[3] On the basis of a custom charge of 20 cents per bale.

No farmer wishes to produce commodities at prices so low as to return him only his cash costs. He wants the best pay he can get for his labor and use of land and equipment. However, if he does not have anything better to do, he may continue to raise broomcorn if it

will return anything over cash costs, even though it is less than a reasonable return on his noncash cost elements. Farmers who had particularly efficient harvest crews or who produced their own seed reduced their cash costs still more. Farmers who employed one hired man during the cropping season increased their preharvest cash costs by approximately 93 cents per acre.

Of the expenses in broomcorn production harvesting constitutes by far the greatest proportion of the cash costs. According to the standards set up in Table 14, tabling and cutting alone, which is entirely a cash cost, amounted to 19 per cent of the total cost of producing broomcorn in 1928. Because of the large amount of labor required for the harvest operations and the necessity for their timely performance it is difficult to reduce the cash cost of these operations.

In the case of broomcorn, if a considerable acreage is grown the large cash expense involves a large total farm expenditure and hence a greater element of risk than in the case of corn, for in the case of corn the cash cost of production per acre, as well as the total cost, is materially less. Assuming a yield of broomcorn of 600 pounds per acre and a price of $150 per ton, approximate averages on the farms visited in 1928, the net return above total costs was approximately $8.50 per acre and above cash costs about $26.

ANNUAL BROOMCORN YIELDS

The yield of broomcorn is influenced by a number of factors such as soil fertility, weather, insects, fungous diseases, stand, crop management, etc., and is a factor of great importance in determining the profits from broomcorn production. Yields of broomcorn on the 100 farms visited in east-central Illinois averaged 583 pounds to the acre for the 5-year period 1924–1928. The average yield per acre on these selected farms was 636 pounds in 1924, 618 pounds in 1925, 520 pounds in 1926, 507 pounds in 1927, and 632 pounds in 1928. In most years they were somewhat higher than the corresponding yield for the State as a whole. The average of the 100 farms for 1928 (632 pounds) reflects a wide range in yield as follows:

Yield group, pounds per acre:	Number of farms
100 and under	0
101–200	1
201–300	3
301–400	5
401–500	13
501–600	19
601–700	33
701–800	17
Over 800	9

On the basis of the average price of $149 per ton received for standard broomcorn in 1928 on the farms visited, the quantity of broomcorn required to cover cost of production, including interest charges, was 488 pounds per acre. If interest charges are excluded, about 386 pounds per acre would cover total costs. About 260 pounds would cover the cash costs as shown in Table 14.

VARIATION IN LABOR AND POWER REQUIREMENTS

There is considerable variation in the labor and power requirements in producing an acre of broomcorn. On 100 broomcorn farms the preharvest man-labor requirements varied from 1.7 to 13.3 man-hours per acre. Horse-hour requirements varied from 3.8 to 36 hours per acre. The majority of the farms studied showed man-labor require-

ments of from 8 to 10 hours per acre; also a considerable number of farms were represented in the class having man-hour requirements of 4 to 6 and 6 to 8 man-hours per acre. A considerable part of this variation is due to differences in land preparation and cultivation and, more particularly with reference to hours of horse work, to whether tractor or horse-drawn implements are utilized. Replanting, where necessary, required considerable extra labor. On a majority of the farms tractor power was used for plowing and disking and on approximately one-fourth of the farms 2-row cultivators were used. The use of a 2-row cultivator, as compared with the 1-row machine, resulted in the saving of slightly more than 1.5 man-hours and nearly 1 horse-hour per acre. The average man hours for plowing with tractor-drawn plows were 1.1 less per acre than when this operation was performed with horse-drawn plows, and 1.3 hours of tractor power were required as against 9.9 hours of horse work. A similar relation with regard to man labor and horse work exists when tractor-drawn disks were used. (Table 15.)

TABLE 15.—*Comparison of requirements per acre of major field operations when done with horse and when done with tractor power in east-central Illinois*

Operation	Man and horse			Man and tractor		
	Reports studied	Hours per acre		Reports studied	Hours per acre	
		Man	Horse		Man	Tractor
Plowing	28	2.4	9.9	66	1.3	1.3
Disking	27	1.8	7.4	72	1.0	1.0
Cultivating, 1-row	73	3.4	6.8	1	2.0	2.0
Cultivating, 2-row	25	1.8	6.0	1	.6	.6

By far the greatest amount of man labor is used in harvesting and marketing broomcorn. The man labor required for this work constituted 80 per cent of the total labor involved in producing and marketing the crop. The harvest man-labor requirements varied from 17.4 to 60.5 man-hours per acre. Horse-hour requirements varied from 1.9 to 14.9 hours per acre. The majority of the farms had man-labor requirements of 30 to 35 hours per acre. Nearly as much time is required to harvest an acre of low-yielding broomcorn as to harvest a high-yielding crop. Stalks must all be tabled in order to facilitate the bunching and hauling of the brush, but in high-yielding fields less sorting and discarding of poor heads is necessary. If broomcorn lodges badly the labor in harvesting is so great that the crop often is abandoned.

Yield per acre is the factor exerting the greatest influence on the man-labor required per unit of product. The influence of yield on the man-hours per ton required to harvest broomcorn is illustrated in Figure 9. In general, as the yield per acre increased, the man-hours per ton decreased. The range in yield was from 130 to 880 pounds per acre. The average yield was 583 pounds per acre. The labor for harvesting broomcorn by growers who had yields of less than 300 pounds per acre varied from 176 to 261 man-hours per ton. Those who had yields of over 700 pounds per acre required only 45 to 150 man-hours per ton, or an average of less than 100 man-hours to harvest the crop.

KANSAS

Southwestern Kansas, typified by Seward and Stevens Counties, produces both standard and dwarf broomcorn. The standard varieties vary in height from 7 to 11 feet; dwarf varieties usually attain a height of from 4 to 6 feet. The annual precipitation in this section is about 18 to 20 inches. Usually very little rainfall occurs during the broomcorn harvesting period, and most of the broomcorn is cured in ricks in the open.

Broomcorn is produced principally on soils that are too sandy for successful wheat production. It usually occupies part of the acreage that would otherwise be devoted to grain sorghums, the major competing cash crop, and is usually grown in rotation with sorghums, corn, or wheat but is sometimes grown on the same land for two or more consecutive years. It is usually produced on land that grew grain sorghums the previous year.

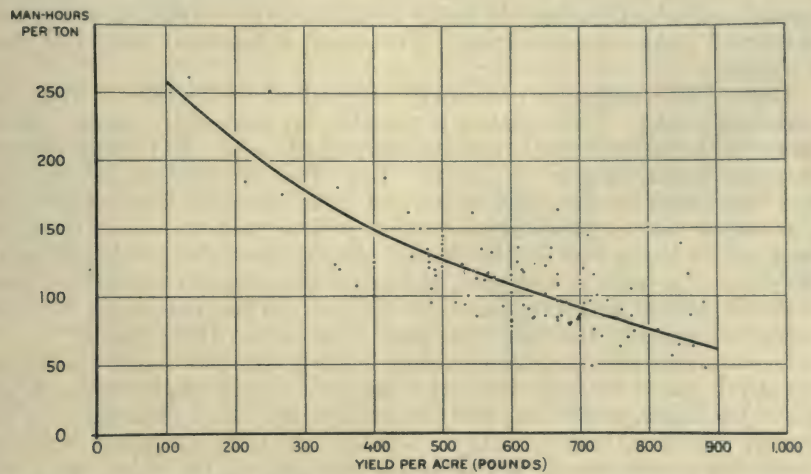


FIGURE 9.—YIELD PER ACRE AND MAN-HOURS PER TON REQUIRED TO HARVEST BROOMCORN IN EAST-CENTRAL ILLINOIS

Each dot represents one farm and its position indicates the yield per acre and the man-hours per ton required to harvest broomcorn on that farm. Those farmers with high yields handled their broomcorn with far less labor per ton than did those with low yields.

USUAL FIELD PRACTICE IN GROWING BROOMCORN AND THE MAJOR COMPETING CASH CROP

The methods of growing broomcorn in southwestern Kansas are similar to those used in growing grain sorghums. Practically the same implements are used in preparing the seed bed, in planting, and in cultivating; and the preharvest cost of the sorghums is essentially the same as that of broomcorn. Thirty-two of the fifty-three growers interviewed in Kansas listed their land when preparing for broomcorn, 8 plowed, and 13 disked without plowing. Most of the listing is done with horse-drawn machines and most of the plowed land is disked and harrowed before planting. The listed land is commonly listed again and planted at the same time by using the planting attachment on the lister. Most of the growers use 2-row lister planters. Most of the broomcorn is planted during the first half of June and the remainder at any time between May 1 and early July.

The usual rate of planting both broomcorn and milo is 1 bushel per 20 to 24 acres.

Broomcorn harvest begins about the last of August and continues through September and most of October. When standard broomcorn attains a height of 8 or 9 feet, it is tabled, as it is in Illinois and Oklahoma. Usually the Black Spanish variety, the one generally grown under limited moisture conditions in Kansas, does not attain a height sufficient to form a good table. The most common method of harvesting standard broomcorn therefore, is to break the upper part of the stalk at a height of about 5 feet. This leaves the brush suspended downward at a convenient height for cutting the stem. The usual practice is to walk along the row and break the stalks forward. When the end of the row is reached the harvester turns around and cuts back along the row. When the stalks do not exceed 7 feet in height the brush is frequently cut from the standing stalks without breaking. Only rarely is standard broomcorn pulled from the stalk. The corn binder is used only when the labor available is not sufficient to harvest the brush before it is overripe. The brush is later cut from the stalk by hand.

Dwarf broomcorn is practically all pulled or "jerked" from the standing stalks. This method is possible because of the weak attachment at the base of the brush handle or peduncle. In pulling broomcorn the worker grasps the top or "flag" leaf of the stalk in one hand and the brush in the other hand and pulls outward with each hand. The hands thus separate with a quick jerking motion and at the same time give a sharp pull on the brush. As the handle of the brush snaps free from the stalk at the base, the brush is separated from the sheath with the proper length of handle attached. When the brush does not mature uniformly the fields are gone over two or three times.

In western Kansas shed curing is not common, and the brush usually is piled directly from the wagon in ricks about 4 feet wide, 3 to 5 feet high, and of any convenient length. As a protection to the brush, which otherwise might absorb ground moisture, timbers, fodder, or straw usually are placed on the ground on which the brush is ricked. The brush is laid with the seed ends outward to the sides in two tiers running the length of the rick with the butts or handles overlapping slightly. Some brush is laid lengthwise in the center of the rick to keep the middle full. The rick is topped out by increasing the lap of the butts to fill the middle and draw in the sides and finally by laying a single tier. The brush is allowed to cure in the rick two to three weeks before it is threshed and baled.

Threshing and baling is done with the same kind of machines as in Illinois, but the brush is cured with the seed attached. Threshing and baling are done at the same time, the bunches of brush being carried directly from the thresher to the baler.

The harvesting of milo, the chief competing cash crop in this area, is accomplished with far less labor than is required for broomcorn. The common method of harvesting milo consists of cutting the heads from the standing stalks and hauling to ricks, from which it is later threshed; then the grain is hauled to market. This method of harvesting milo requires approximately one-fourth the man labor required to harvest an acre of broomcorn. The labor in harvesting milo can be further reduced by the less common practice of using a header or combine.

PRACTICES THAT SHOULD INCREASE PROFITS

In most instances broomcorn growers would profit by the use of better seed. At the time of this study many of the fields were not pure, or they contained smutty broomcorn. Broomcorn seed should be fully mature and should be obtained from a field of a pure and uniform variety grown at some distance from any other sorghum field. All seed should be treated for smut unless it is known to be free from this disease.

Experiments conducted at the Oklahoma Dry Land Field Station at Woodward show that Scarborough broomcorn produces a better quality of brush and yields better than the Evergreen Dwarf (Oklahoma dwarf variety). Either of these dwarf varieties will outyield the Black Spanish standard variety except under conditions of drought or early frost but may be inferior in quality. (*14*)

Prompt harvesting would result in a better quality of brush than is frequently obtained in western Kansas but necessitates the hiring of additional labor and increases somewhat the cash cost of harvesting.

In most seasons shed curing and threshing before curing will result in a price for the brush more than sufficient to cover the additional expense.

Sheds suitable for broomcorn storage can be built at an expense ranging from $30 to $40 per ton capacity. Slats necessary for a ton of brush at 7 cents each cost about $18.50. Allowing for insurance, depreciation, repairs, replacements of slats, interest on the investment, and about three man-hours per ton additional labor to shed the brush, the additional cost of shed-cured over rick-cured brush should not exceed $4.50 to $5 per ton, if the shed is filled twice each season. In an ordinary season shed-cured brush usually sells at $5 to $10 per ton higher than rick-cured brush because of less bleaching and better threshing of the shed-cured crop. In wet seasons such as 1930, however, the brush may be so damaged from exposure in either the rick or bale that the price is cut $20 to $40 per ton. In such years the saving as a result of shed curing the brush would pay for the additional cost of shed curing for several seasons. In a very favorable harvesting season shed-cured brush sells for about the same price as rick-cured brush. Only 9 of the 53 growers interviewed in Kansas shed-cured any of their broomcorn in 1928.

COST OF PRODUCTION

In southwestern Kansas, where it is not the general custom to shed-cure the brush and where less tillage and less cultivation are required, the requirements of man labor and horse work are somewhat less than in the more intensive standard broomcorn sections. For a yield of 333 pounds of standard broomcorn per acre about 24 hours of man labor and 17 hours of horse work per acre are required. These requirements amount to 145 hours of man labor and about 104 hours of horse work per ton. (Table 16.) The labor in harvesting dwarf broomcorn is about 15 man-hours less per ton than for standard broomcorn.

Materials such as seed and baling wire cost about 25 cents per acre or $1.50 per ton.

Other costs, including taxes, use of machinery, loss on abandoned acreage, and overhead expense, amount to about $2 per acre.

In 1928 broomcorn land was valued at $25 per acre in southwestern Kansas. Interest charges are frequently considered a part of production costs and when figured at 5 per cent of this land value they amount to $1.25 per acre.

TABLE 16.—*Cost of producing standard broomcorn brush, according to the usual field practice and at cost rates prevailing in 1928* [1] *in southwestern Kansas*

Item	Size of crew		Rate of work per day	Times operation is performed	Quantity and cost [2]					
					Per acre			Per ton		
	Men	Horses			Man-hours	Horse-hours	Cost	Man-hours	Horse-hours	Cost
Labor and power:										
Preharvest—			*Acres*							
List (2-row lister)	1	6	16	1	0.6	3.6	$0.48	3.6	21.6	$2.88
Plant (2-row lister)	1	6	16	1	.6	3.6	.48	3.6	21.6	2.88
Throw out (2-row curler)	1	4	16	1	.6	2.4	.36	3.6	14.4	2.16
Harrow (2-section 9-foot)	1	4	20	1	.5	2.0	.30	3.0	12.0	1.80
Throw in (2-row curler)	1	4	16	1	.6	2.4	.36	3.6	14.4	2.16
Miscellaneous					.8	.8	.24	4.8	4.8	1.44
Harvest [3]—										
Break and cut [4]	7		5	1	14.0		5.60	84.0		33.60
Haul and rick (wagon)	2	2	9	1	2.2	2.2	1.10	13.2	13.2	6.60
Seed and bale—			*Tons*							
Farm crew	18		9½	1	3.2	.3	1.28	19.2	1.8	7.68
Contract [5] (power seeder)	2	2			.3		.90	1.8		5.40
Haul to market (contract, 12 miles with truck) [6]	1			1	.3		.40	1.8		2.40
Miscellaneous					.5		.20	3.0		1.20
Total					24.2	17.3	11.70	145.2	103.8	70.20
Materials:										
Seed 2½ pounds at 6 cents per pound							.15			.90
Bailing wire							.10			.60
Total							.25			1.50
Other costs:										
Taxes							.30			1.80
Use of machinery							.22			1.32
Loss on abandoned acreage							.12			.72
Overhead							1.35			8.10
Total							1.99			11.94
Total cost exclusive of interest							13.94			83.64
Interest on land, at 5 per cent							1.25			7.50
Total cost including interest							15.19			91.14

[1] Man labor, previous to harvest, is charged at 20 cents per hour, harvest labor except that done on a contract basis at 40 cents per hour, and horse work at 10 cents per hour.

[2] Based on a yield of 333 pounds per acre.

[3] All work done on a contract basis has been reduced to hours of man labor and horse work, but is charged at the contract rate for such work.

[4] Dwarf broomcorn is pulled from the standing stalk which requires about 70 man-hours per ton for a 333 pound per acre yield, or in 1928 a cost of $28 per ton, as against $33.60 for breaking and cutting. In other respects the cost of producing dwarf broomcorn is practically the same as for standard broomcorn.

[5] Charged at the custom rate of 90 cents per bale of 333 pounds.

[6] Charged at the custom rate of 40 cents per bale of 333 pounds.

Including interest on land the total cost in 1928 was about $15 per acre. On the basis of a yield of 333 pounds per acre the cost per ton amounted to $91. Excluding interest charges the cost per acre amounted to about $14. The 5-year average yield (1924–1928) for

the 53 farms visited was 295 pounds per acre. The average for 1928, 329 pounds per acre, reflects a wide range in yields as follows:

Yield group, pounds per acre:	Number of farms
100 and under	1
101–200	4
201–300	18
301–400	19
401–500	7
501–600	1
Over 600	3

About one-third of these growers had yields of from 300 to 400 pounds per acre in 1928. Where yields are the same, because of less labor in harvesting, the cost of producing dwarf broomcorn is about $6 per ton less than that of standard broomcorn. Costs in southwestern Kansas are similar to those in Colorado, New Mexico, and northwestern Oklahoma.

Growers who have no indebtedness, hire no preharvest labor, hire no field boss, exchange labor for seeding and baling and haul the crop to market themselves could produce broomcorn in 1928 for an actual cash outlay of approximately 49 per cent of the total cost of production. (Table 17.) This applies more particularly to farmers with medium acreages who do not have to hire preharvest labor. Farmers who had particularly efficient harvest crews or who produced their own seed reduced their cash costs still more. Farmers who employed one hired man during the cropping season increased their cash costs by about 37 cents per acre.

TABLE 17.—*Estimated cash and noncash cost per acre of producing broomcorn in southwestern Kansas, 1928* [1]

Item	Cash cost per acre		Noncash cost per acre	
	Dollars	*Per cent*	*Dollars*	*Per cent*
Preharvest:				
Man labor			0.74	4.9
Horse work			1.48	9.7
Harvest:				
Break and cut [2]	4.80	31.6	.80	5.3
Haul and rick [3]	.44	2.9	.66	4.4
Seed and bale [4]	.90	5.9	1.28	8.4
Haul to market			.40	2.6
Miscellaneous			.20	1.3
Materials:				
Seed	.15	1.0		
Baling wire	.10	.7		
Other costs:				
Taxes	.30	2.0		
Use of machinery	.11	.7	.11	.7
Loss on abandoned acreage			.12	.8
Overhead	.67	4.4	.68	4.5
Interest on land			1.25	8.2
Total	7.47	49.2	7.72	50.8

[1] On the basis of the grower owning his land and equipment free from indebtedness and hiring no help previous to harvest. If 1 man is hired previous to harvest the cash cost of preharvest labor would be approximately 37 cents per acre.

[2] On a basis of a cash expense for 5/7 of the harvest labor.

[3] On the basis of a cash expense for ½ of the man labor.

[4] On the basis of a custom charge of 90 cents per bale and exchange labor for the farm crew.

Breaking and cutting constitute by far the greater proportion of the cash costs of producing broomcorn. According to standards set up in Table 17 this item amounted to nearly two-thirds of the cash cost of producing broomcorn in 1928.

On the basis of the average 1928 price of $111 per ton received for standard broomcorn on the farms visited in Kansas, the quantity of broomcorn required to cover total cost of production, including interest charges, was 274 pounds per acre and, excluding interest charges, 251 pounds per acre. One hundred thirty-five pounds per acre would cover the cash costs as shown in Table 17.

Where a considerable acreage of broomcorn is grown the large expense for harvesting entails a large total farm expenditure and involves a greater element of risk than in the case of milo. With milo the cash cost of production per acre as well as the total cost is materially less than in the case of broomcorn. Assuming a yield of broomcorn of 333 pounds per acre and a price of $111 per ton, which were approximate averages on the farms visited in 1928, the net returns above total costs were about $3.30 per acre and above cash costs $11.

OKLAHOMA

The so-called "Lindsay district" in Garvin and McClain Counties, south-central Oklahoma, has long been recognized as a source of high-quality standard broomcorn brush. The average annual precipitation is about 33 inches. Rains during the broomcorn-harvest season are frequent enough to necessitate the use of sheds for storing and curing the brush. The soils in the river valley near Lindsay are mostly a dark sandy loam with some gumbo. Gray loam soils predominate on the uplands.

Broomcorn is usually grown in a rotation with corn and cotton, although it is sometimes grown on the same land for two or more consecutive years.

USUAL FIELD PRACTICE IN GROWING BROOMCORN AND THE MAJOR COMPETING CASH CROP

Of 36 growers interviewed, 26 plowed, 9 listed, and 1 disked as the first step in preparing the seed bed for broomcorn. Two-bottom horse-drawn plows are common. Following plowing, most of the land was disked and harrowed before planting. A majority of growers use 1-row lister planters, but on some farms 2-row corn planters with disk furrow opener attachments are used for planting broomcorn.

The preharvest work in preparing the seed bed, and planting and cultivating cotton is essentially the same as for broomcorn except that cotton is usually given two more cultivations and is generally hoed twice. These added operations result in a preharvest cotton labor and power requirement per acre that is about 13 man-hours and approximately 5 horse-hours greater than for broomcorn.

The usual rate of planting broomcorn is 1 bushel of seed to 12 to 16 acres on the bottom lands. Planting begins the last of March and continues until July, most of the planting being done in April.

The method of harvesting broomcorn is very similar to that employed in Illinois. Harvesting begins in July and continues through September. All of the crop is tabled and cut and hauled from the field. The brush is seeded before being cured and is placed in curing sheds as in Illinois. Baling begins 10 to 21 days after the brush is put in the shed. Curing sheds are built with the stalls running crosswise of the shed, whereas the stalls in most of the sheds in Illinois

run lengthwise of the sheds. The crop is all baled directly from the slats even though the sheds are filled two or three times.

The total man labor and horse work required to produce and market an acre of cotton yielding 200 pounds per acre is approximately 55 man-hours and 38 horse-hours. In the case of cotton the preharvest man-hours are considerably greater than for broomcorn, whereas the harvest man-hours are slightly fewer.

PRACTICES THAT SHOULD INCREASE PROFITS

Farmers generally recognize that planting with a corn planter is conducive to better stands than is lister planting. Much of the broomcorn is planted in the Lindsay district in April and early May. Experiments have shown that higher yields are usually obtained from planting after than before May 15 (*14*).

Black Spanish broomcorn usually produces a rather short brush and yields less than the standard Evergreen variety. Growers should consider carefully the question whether the lower yields of the Black Spanish variety are compensated by a sufficiently higher selling price.

The price of $10 per bushel for broomcorn seed in 1928 was a considerably higher cost expenditure than was necessary. Pure locally grown certified seed could be obtained at not more than one-half the price paid for seed shipped in from Illinois. More Oklahoma farmers should specialize in the growing of high-quality broomcorn seed for planting in their State.

Man labor previous to harvest could be materially reduced by the use of larger implements, as is shown by lower labor requirements in Illinois and Kansas, where the use of 2-row planters and other large implements is common. (Tables 13 and 16.) Another practice conducive to economical production of broomcorn would be the paying of harvest labor by the acre, as is common in Illinois, instead of by the hour. A considerable saving in the cost of harvesting broomcorn may easily be effected by the increased output per man when payment is made on the contract-acre basis.

COST OF PRODUCTION

In south-central Oklahoma, where the yield is slightly less than in Illinois and where it is not the usual practice to use tractor power, the man labor per acre amounted to about 44 hours and the horse work to about 38 hours for a yield of 500 pounds per acre. On a ton basis it takes about 175 hours of man labor and 152 hours of horse work. (Table 18.)

TABLE 18.—*Cost of producing standard broomcorn brush according to the usual field practices and at cost rates prevailing in 1928,*[1] *in south-central Oklahoma*

Item	Size of crew		Rate of work per day	Times operation is performed	Quantity and cost [2]					
					Per acre			Per ton		
	Men	Horses			Man-hours	Horse-hours	Cost	Man-hours	Horse-hours	Cost
Labor and power:										
Preharvest—			*Acres*							
Plow (2-bottom 14-inch)	1	4	4	1	2.5	10.0	$1.44	10.0	40.0	$5.75
Disk or single list (7-foot double disk or 1-row lister)	1	4	8	1	1.3	5.2	.75	5.2	20.8	2.99
Harrow (2-section 9-foot)	1	4	20	1	.5	2.0	.29	2.0	8.0	1.15
Plant (1-row lister)	1	4	8	1	1.3	5.2	.75	5.2	20.8	2.99
Cultivate (1-row riding)	1	2	8	3	3.8	7.6	1.42	15.2	30.4	5.70
Miscellaneous					1.0	.8	.25	4.0	3.2	1.02
Harvest [3]—										
Table and cut	24		12	1	20.0		7.00	80.0		28.00
Haul to shed	4	4	13	1	3.1	3.1	1.40	12.4	12.4	5.58
Seed and shed—			*Tons*							
Farm crew	25		15	1	4.2		1.47	16.8		5.88
Contract [4] (power seeder)	1				.2		1.50	.8		6.00
Bale—										
Farm crew	11		10	1	2.8	.4	.98	11.2	1.6	3.92
Contract [5]	1	2			.2		.60	.8		2.40
Haul to market (5 miles) with wagon	1	2	3	1	.8	1.6	.44	3.2	6.4	1.76
Roustabout	1	2			1.0	2.0	.55	4.0	8.0	2.20
Supervision	1				.8		.40	3.2		1.60
Miscellaneous					.4		.14	1.6		.56
Total					43.9	37.9	19.38	175.6	151.6	77.50
Materials:										
Seed 3½ pounds at 21 cents per pound							.70			2.80
Baling wire							.15			.60
Total							.85			3.40
Other costs:										
Taxes							2.00			8.00
Fire insurance on brush [6]							.41			1.64
Use of machinery							.54			2.16
Use of broomcorn shed							1.39			5.56
Loss on abandoned acreage							.73			2.92
Overhead							2.39			9.56
Total							7.46			29.84
Total cost exclusive of interest							27.69			110.74
Interest on land at 5 per cent							6.25			25.00
Total cost, including interest							33.94			135.74

[1] Man labor previous to harvest charged at 17½ cents per hour, harvest work, except that done on a contract basis, at 35 cents per hour, supervision at 50 cents per hour, and horse work at 10 cents per hour.
[2] Based on a yield of 500 pounds per acre.
[3] All work done on a contract basis has been reduced to hours of man labor and horse work but is charged at the contract rate for such work.
[4] Charged at the custom rate of $1 per bale of 333 pounds.
[5] Charged at the custom rate of 40 cents per bale of 333 pounds.
[6] Based on a premium rate of $1.10 per $100 of valuation for the first month and at 55 cents per $100 of valuation for the second month.

Materials such as seed and baling wire amount to 85 cents per acre or $3.40 per ton.

Other costs, including taxes, fire insurance on the brush, use of machinery, use of broomcorn shed, losses due to abandoned acreage, and overhead expenses, amount to about $7.50 per acre.

Including interest on land value, the total cost in 1928 was $34 per acre. Excluding interest charges, the cost per acre amounted to about $27.70. The cost per ton amounted to about $136 on the basis of a yield of 500 pounds per acre. This yield is somewhat higher than the average for the State but is representative of average yields obtained on the better broomcorn soils. The yields obtained on the 36 farms visited averaged 419 pounds per acre in 1928. The 5-year average yield (1924–1928) was 484 pounds per acre. In 1928 about one-third of the growers had yields of from 400 to 500 pounds per acre. The range in yield on these farms was as follows:

Yield group, pounds per acre:	Number of farms
100 and under	0
101–200	1
201–300	7
301–400	9
401–500	11
501–600	6
Over 600	2

Broomcorn growers who have no indebtedness, hire no preharvest labor, hire no field boss, exchange labor for baling, and haul the crop to market themselves could produce broomcorn in 1928 for an actual cash outlay of approximately 50 per cent of the total cost of production. (Table 19.) This applies more particularly to farmers with medium acreages who do not have to hire preharvest labor. Farmers who had particularly efficient harvest crews or who produced their own seed reduced their cash costs. Farmers who employed one hired man during the cropping season increased their preharvest cash costs in Oklahoma by about 91 cents per acre.

TABLE 19.—*Estimated cash and noncash cost per acre of producing broomcorn in south-central Oklahoma, 1928* [1]

Item	Cash cost per acre		Noncash cost per acre	
	Dollars	*Per cent*	*Dollars*	*Per cent*
Preharvest:				
Man labor			1.82	5.4
Horse labor			3.08	9.1
Harvest:				
Table and cut	7.00	20.6		
Haul to shed [2]	1.09	3.2	.31	.9
Seed and shed	2.97	8.7		
Bale [3]	.60	1.8	.98	2.9
Haul to market			.44	1.3
Supervision			.40	1.2
Roustabout			.55	1.6
Miscellaneous			.14	.4
Materials:				
Seed	.70	2.1		
Baling wire	.15	.4		
Other costs:				
Taxes	2.00	5.9		
Fire insurance on brush	.41	1.2		
Use of machinery	.27	.8	.27	.8
Use of broomcorn shed	.70	2.1	.69	2.0
Loss on abandoned acreage			.73	2.2
Overhead	1.19	3.5	1.20	3.5
Interest on land			6.25	18.4
Total	17.08	50.3	16.86	49.7

[1] On the basis of the grower owning his land and equipment free from indebtedness and hiring no help previous to harvest. If 1 man is hired previous to harvest the cash cost of preharvest labor would be approximately 91 cents per acre.
[2] On the basis of a cash expense for all of the man labor.
[3] On the basis of a custom charge of 40 cents per bale.

Of the cash expense in broomcorn production, that of tabling and cutting constitutes by far the greater part of the cash costs. According to the standards set up in Table 19, this item amounted to about 40 per cent of the cash cost of producing broomcorn in Oklahoma in 1928.

Although the total labor requirements for growing cotton are somewhat higher than those for growing broomcorn, the large cash expenditure at harvest time, when a considerable acreage is grown, makes the element of risk greater than in the case of cotton, where harvesting work can be extended over a relatively longer period and affords a greater opportunity for the use of family labor.

On the basis of an average farm price of $150 in 1928, the quantity of broomcorn required to cover cost of production, including interest charges, was 453 pounds per acre. Excluding interest charges, about 369 pounds per acre would cover total costs, and about 227 pounds per acre would cover the cash costs.

CHOICE OF COMPETING CASH CROPS

In each of the three districts studied there is another major cash crop which is in direct competition with broomcorn for the farm acreage. In Illinois this major competing cash crop is corn, in Kansas it is kafir and milo, and in Oklahoma it is cotton. (Table 12.) The comparative acreage devoted to broomcorn and the competing cash crop in each district changes materially from year to year; it depends mainly on the farmer's judgment as to which one will return the greater profit.

In selecting his crop enterprises a broomcorn grower should carefully consider the conditions under which he works, such as his financial resources, equipment for growing broomcorn and other crops, keeping his labor and power profitably employed, feed requirements for his livestock, and the like. He should attempt to adjust his crop acreage in such a manner as to realize the greatest net returns for his labor and management.

Relative net return per acre is only one of several factors that should be considered, but in the case of broomcorn and the major competing cash crop in each district, net return per acre as a measure of the choice of crop enterprises has many things in its favor. Broomcorn and its rivals are intertilled crops and, prior to harvest, require the attention of the farmer at the same time of the year, require the same tillage implements, and there is little difference in effects in increasing or decreasing the productiveness of the soil. Another factor that influences choice of crops is the personal likes or dislikes of farmers. Many farmers dislike to grow broomcorn because of a skin irritation caused by the fine hairs which are separated from the broomcorn chaff in threshing. Most farmers can overcome personal preference, however, if by so doing they can make more money.

NET RETURNS PER ACRE FROM BROOMCORN AND COMPETING CASH CROPS

The net returns per acre with different yields and prices for broomcorn and the major competing cash crop in each district are shown in Tables 20, 21, 22, 23, 24, and 25. The costs as shown are those of 1928; costs have receded somewhat since that time. The prices shown include those in 1928 as well as those in effect at present. The estimated net returns per acre were determined by subtracting

from the gross returns at the prices indicated, the cost of producing the different crops. The preharvest cost of growing broomcorn and the competing cash crop in each district is nearly the same. The differences in production costs are chiefly due to the influence of yield on the cost of harvesting and marketing the several crops. For each crop, costs up to harvest have been held constant regardless of yield. As an example of the application of these data, the comparative net returns from broomcorn and the major competing cash crop in each district will be examined.

TABLE 20.—*Net returns per acre from broomcorn, computed at stated yields and prices and at cost rates prevailing in 1928 in east-central Illinois*

Farm price per ton	Net returns per acre when yield is—					
	300 pounds costing $32.93	400 pounds costing $34.06	500 pounds costing $35.19	600 pounds costing $36.32	700 pounds costing $37.45	800 pounds costing $38.58
Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
60	−23.93	−22.06	−20.19	−18.32	−16.45	−14.58
80	−20.93	−18.06	−15.19	−12.32	−9.45	−6.58
100	−17.93	−14.06	−10.19	−6.32	−2.45	1.42
120	−14.93	−10.06	−5.19	−.32	4.55	9.42
140	−11.93	−6.06	−.19	5.68	11.55	17.42
160	−8.93	−2.06	4.81	11.68	18.55	25.42
180	−5.93	1.94	9.81	17.68	25.55	33.42
200	−2.93	5.94	14.81	23.68	32.55	41.42

TABLE 21.—*Net returns per acre from corn, computed at stated yields and prices and at cost rates prevailing in 1928 in east-central Illinois*

Farm price per bushel	Net returns per acre when yield is—						
	25 bushels costing $22.76	30 bushels costing $23.53	35 bushels costing $24.29	40 bushels costing $25.05	45 bushels costing $25.81	50 bushels costing $26.57	55 bushels costing $27.43
Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
0.20	−17.76	−17.53	−17.29	−17.05	−16.81	−16.57	−16.43
.30	−15.26	−14.53	−13.79	−13.05	−12.31	−11.57	−10.93
.40	−12.76	−11.53	−10.29	−9.05	−7.81	−6.57	−5.43
.50	−10.26	−8.53	−6.79	−5.05	−3.31	−1.57	.07
.60	−7.76	−5.53	−3.29	−1.05	1.19	3.43	5.57
.70	−5.26	−2.53	.21	2.95	5.69	8.43	11.07
.80	−2.76	.47	3.71	6.95	10.19	13.43	16.57
.90	−.26	3.47	7.21	10.95	14.69	18.43	22.07
1.00	2.24	6.47	10.71	14.95	19.19	23.43	27.57

TABLE 22.—*Net returns per acre from broomcorn, computed at stated yields and prices and at cost rates prevailing in 1928 in southwestern Kansas*

Farm price per ton	Net returns per acre when yield is—						
	200 pounds costing $13.90	250 pounds costing $14.37	300 pounds costing $14.84	350 pounds costing $15.31	400 pounds costing $15.78	450 pounds costing $16.25	500 pounds costing $16.72
Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
40	−9.90	−9.37	−8.84	−8.31	−7.78	−7.25	−6.72
60	−7.90	−6.87	−5.84	−4.81	−3.78	−2.75	−1.72
80	−5.90	−4.37	−2.84	−1.31	.22	1.75	3.28
100	−3.90	−1.87	.16	2.19	4.22	6.25	8.28
120	−1.90	.63	3.16	5.69	8.22	10.75	13.28
140	.10	3.13	6.16	9.19	12.22	15.25	18.28
160	2.10	5.63	9.16	12.69	16.22	19.75	23.28
180	4.10	8.13	12.16	16.19	20.22	24.25	28.28

TABLE 23.—*Net returns per acre from milo, computed at stated yields and prices and at cost rates prevailing in 1928 in southwestern Kansas*

Farm price per bushel	Net returns per acre when yield is—								
	10 bushels costing $8.29	15 bushels costing $8.86	20 bushels costing $9.45	25 bushels costing $10.40	30 bushels costing $10.98	35 bushels costing $11.56	40 bushels costing $12.68	45 bushels costing $13.26	50 bushels costing $13.84
Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
0.20	−6.29	−5.86	−5.45	−5.40	−4.98	−4.56	−4.68	−4.26	−3.84
.30	−5.29	−4.36	−3.45	−2.90	−1.98	−1.06	−.68	.24	1.16
.40	−4.29	−2.86	−1.45	−.40	1.02	2.44	3.32	4.74	6.16
.50	−3.29	−1.36	.55	2.10	4.02	5.94	7.32	8.24	11.16
.60	−2.29	.14	2.55	4.60	7.02	9.44	11.32	13.74	16.16
.70	−1.29	1.64	4.55	7.10	10.02	12.94	15.32	18.24	21.16
.80	−.29	3.14	6.55	9.60	13.02	16.44	19.32	22.74	26.16
.90	.71	4.64	8.55	12.10	16.02	19.94	23.32	27.24	31.16

TABLE 24.—*Net returns per acre from broomcorn, computed at stated yields and prices, and at cost rates prevailing in 1928 in south-central Oklahoma*

Farm price per ton	Net returns per acre when yield is—					
	200 pounds costing $28.60	300 pounds costing $30.38	400 pounds costing $32.16	500 pounds costing $33.94	600 pounds costing $35.72	700 pounds costing $37.50
Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
60	−22.60	−21.38	−20.16	−18.94	−17.72	−16.50
80	−20.60	−18.38	−16.16	−13.94	−11.72	−9.50
100	−18.60	−15.38	−12.16	−8.94	−5.72	−2.50
120	−16.60	−12.38	−8.16	−3.94	.28	4.50
140	−14.60	−9.38	−4.16	1.06	6.28	11.50
160	−12.60	−6.38	−.16	6.06	12.28	18.50
180	−10.60	−3.38	3.84	11.06	18.28	25.50
200	−8.60	−.38	7.84	16.06	24.28	32.50

TABLE 25.—*Net returns per acre from cotton, computed at stated yields and prices and at cost rates prevailing in 1928 in south-central Oklahoma*

Farm price per pound	Net returns per acre when yield is—								
	100 pounds costing $21.06	150 pounds costing $22.17	200 pounds costing $23.28	250 pounds costing $24.39	300 pounds costing $25.50	350 pounds costing $26.61	400 pounds costing $27.72	450 pounds costing $28.83	500 pounds costing $29.94
Dollar	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
0.06	−15.06	−13.17	−11.28	−9.39	−7.50	−5.61	−3.72	−1.83	0.06
.07	−14.06	−11.67	−9.28	−6.89	−4.50	−2.11	.28	2.67	5.06
.08	−13.06	−10.17	−7.28	−4.39	−1.50	1.39	4.28	7.17	10.06
.09	−12.06	−8.67	−5.28	−1.89	1.50	4.89	8.28	11.67	15.06
.10	−11.06	−7.17	−3.28	.61	4.50	8.39	12.28	16.17	20.06
.11	−10.06	−5.67	−1.28	3.11	7.50	11.89	16.28	20.67	25.06
.12	−9.06	−4.17	.72	5.61	10.50	15.39	20.28	25.17	30.06
.13	−8.06	−2.67	2.72	8.11	13.50	18.89	24.28	29.67	35.06
.14	−7.06	−1.17	4.72	10.61	16.50	22.39	28.28	34.17	40.06
.15	−6.06	.33	6.72	13.11	19.50	25.89	32.28	38.67	45.06
.16	−5.06	1.83	8.72	15.61	22.50	29.39	36.28	43.17	50.06
.17	−4.06	3.33	10.72	18.11	25.50	32.89	40.28	47.67	55.06
.18	−3.06	4.83	12.72	20.61	28.50	36.39	44.28	52.17	60.06
.19	−2.06	6.33	14.72	23.11	31.50	39.89	48.28	56.67	65.06
.20	−1.06	7.83	16.72	25.61	34.50	43.39	52.28	61.17	70.06

In east-central Illinois, with a yield of 600 pounds of broomcorn per acre and a price of $160 per ton and a yield of 40 bushels of corn selling at 70 cents per bushel (which are approximate averages on the

farms visited), the net per-acre advantage of broomcorn over corn amounts to approximately $8.73 per acre. With these yields, corn at 90 cents per bushel would give approximately the same net returns per acre as broom corn at $160 per ton. On the basis of yields of 600 pounds of broomcorn and 40 bushels of corn, prices of approximately $125 per ton for broomcorn and 65 cents per bushel for corn were required in order to show any profit in 1928.

In southwestern Kansas, with a yield of 300 pounds of standard broomcorn per acre and a price of $120 per ton, and a yield of 20 bushels of milo per acre, selling at 70 cents per bushel (approximate averages on the farms visited), the net per-acre advantage of milo over broomcorn amounts to approximately $1.39 per acre. With these yields, broomcorn at $140 per ton would give approximately the same net returns per acre as milo at 80 cents per bushel. On the basis of yields of 300 pounds of broomcorn and 20 bushels of milo, approximately $100 per ton must have been realized for broomcorn and 50 cents per bushel for milo in order to show any profit in 1928.

In the Lindsay district of south-central Oklahoma, with a yield of 500 pounds of broomcorn and a price of $170 per ton and a yield of 200 pounds of cotton selling at 15 cents per pound (approximate averages on the farms visited), the net per-acre advantage of cotton over broomcorn amounts to approximately $1.84 per acre. With these yields, broomcorn at $180 per ton would give approximately the same net returns per acre as cotton at 17 cents per pound. On the basis of a 500-pound yield of broomcorn and a 200-pound yield of cotton, $140 per ton must have been realized from broomcorn and 12 cents per pound from cotton in order to show any profit in 1928.

The cost per acre of producing broomcorn is considerably greater than that of producing corn, milo, or cotton. Broomcorn must be harvested promptly, which involves a large cash expense when production is on a large scale. On the other hand, the harvesting of corn, milo, and cotton can be extended over a considerable period of time and gives a better opportunity than broomcorn for the use of family labor. In addition, on the basis of the average yield that can be expected and with prices any lower than those required to show some profit, the losses from broomcorn would be greater than that from corn, milo, or cotton.

From the management standpoint, broomcorn has an advantage in that it can be harvested in ample time for seeding wheat on the same land and earlier than can corn. From the marketing standpoint corn and milo may be sold or fed to livestock whereas broomcorn and cotton must be sold directly. Because of heavy expenditures for hired labor at harvest time and wide fluctuations in broomcorn prices, broomcorn is more speculative than the competing cash crop in the districts under consideration. On the basis of average yields and prices, broomcorn appears to have had a slight advantage over corn in Illinois, whereas in western Kansas and in the Lindsay district of Oklahoma, the relative net returns from milo and cotton, were slightly greater than from broomcorn.

As is well known, costs vary on individual farms, owing to differences in yields and other contributing factors, and no formula can be set up which will be applicable to all farms. Yield per acre, however, is the principal factor causing variations in costs, and the net returns per acre have been adjusted for the yield factor as well as for price

differences. Having a fair idea of the yield that can be expected and using a price based on the price outlook for the two competing crops, individual farmers should be able to use the data to advantage in adjusting their crop acreage between broomcorn and the competing cash crop.

SUMMARY

The growing of broomcorn on a commercial scale in this country began in the Connecticut Valley at Hadley, Mass., in 1798. Since that time broomcorn production, with the exception of that in east-central Illinois, has gradually shifted westward until, at present, it has become practically concentrated in the Southwest. As broomcorn is drought-resistant, it is adapted to the semiarid conditions of the Plains States, where the choice of cash crops is limited.

The average yield of broomcorn brush in the United States is about 322 pounds per acre. During the 17-year period 1915–1931 the yearly production of broomcorn has fluctuated from 29,500 to 81,000 tons.

Broomcorn competes only slightly with any other commodity whereas a number of products—such as vacuum cleaners and brushes and brooms made of materials other than broomcorn—severly compete with broomcorn brooms. The lack of expansion in the broom industry is primarily due to the increasing competition of these other products, chiefly vacuum cleaners. Since the uses of broomcorn are almost entirely limited to the making of brooms and since the demand for domestic use is satisfied at about 45,500 tons, a supply greater or less than these requirements, plus the annual export demand of approximately 4,500 tons, results in a decided change in the price received. Violent fluctuations in production and prices frequently make broomcorn one of the most speculative of farm crops.

In each district in which cost-of-production studies were made there is a major competing cash crop. In east-central Illinois it is corn (maize); in southwestern Kansas it is grain sorghums, mainly milo, and in south-central Oklahoma it is cotton.

Broomcorn produced on an extensive scale requires more capital than does the major competing cash crop in each of these districts. Some special broomcorn equipment is necessary and a relatively large cash outlay for labor to harvest the crop is essential to successful production of broomcorn.

Costs of producing broomcorn in 1928 in Illinois, Kansas, and Oklahoma ranged from $91 to $136 per ton, of which cash costs represented approximately 50 per cent.

The principal item of cost is man labor. The 5-year average yields for the districts studied ranged from 295 to 583 pounds of brush per acre, while the yields required to pay costs, including interest charges, ranged from 274 to 488 pounds per acre.

On the basis of average yields and prices, broomcorn appears to have had a slight advantage over corn in Illinois whereas the relative net returns from milo in Kansas and cotton in Oklahoma were slightly greater than from broomcorn.

LITERATURE CITED

(1) ANONYMOUS.
1836. A BROOM CORN MANIA. Genesee Farmer and Gard. Jour. 6 (17):135.
(2) ———
1859. BROOM CORN IN ILLINOIS. Genesee Farmer (2) 20:336.
(3) ———
1930. MCPHERSON COUNTY FARMER BROUGHT BROOM CORN TO KANSAS. Broom-corn Rev. 19 (5):9.
(4) ALGUIRE, G. B.
1922. MARKETING BROOM CORN. U. S. Dept. Agr. Bul. 1019, 32 p., illus.
(5) AMERICAN AGRICULTURIST.
1894. BROOM-CORN AND BROOMS. Written and compiled by the editors of the American Agriculturist. New and Rev. ed., 59 p. New York.
(6) BAUHIN, K.
1658. THEATRI BOTANICI SIVE HISTORIAE PLANTARUM EX VETERUM ET RECENTIORUM PLACITIS PROPRIAQ. OBSERVATIONE CINCINNATÆ. 683 col., [36] p., illus. Basileæ.
(7) [FLEMING, S. P.]
1929. ANCIENT LORE ON BROOM CORN. Broom and Broomcorn News 18 (22):8–9.
(8) G., F.
1873. CULTURE OF BROOM CORN. Cult. and Country Gent. 38:643–644.
(9) HEUZE, G.
1893–1895. LES PLANTES INDUSTRIELLES. Ed. 3, 4 v. Paris.
(10) HOWARD, J. R.
1846. FARMING IN OHIO. BROOM CORN. Cultivator (n. s.) 3 (1):21.
(11) JEFFERSON, T.
1853. NOTES OF THE STATE OF VIRGINIA. 275 p., illus. Richmond, Va.
(12) JONES, C.
1905. THE BROOM CORN INDUSTRY IN THE COUNTIES OF FRANKLIN AND HAMPSHIRE, AND IN THE TOWN OF DEERFIELD IN PARTICULAR. *In* History and Proceedings of the Pocumtuck Valley Memorial Association, 1899–1904. v. 4, pp. 105–111. Deerfield.
(13) JUDD, S.
1863. HISTORY OF HADLEY, INCLUDING THE EARLY HISTORY OF HATFIELD, SOUTH HADLEY, AMHERST, AND GRANBY, MASSACHUSETTS. pp. 1–440. Northampton.
(14) SIEGLINGER, J. B.
1928. BROOM CORN EXPERIMENTS AT THE UNITED STATES DRY-LAND FIELD STATION, WOODWARD, OKLA. U. S. Dept. Agr. Tech. Bul. 51. 32 p., illus.
(15) TARBOX, G. S.
1923. A BROOM CORN STORY. Broom and Broom Corn News 12 (1):8.
(16) WATSON, J. F.
1859. ANNALS OF PHILADELPHIA AND PENNSYLVANIA. v. 2, p. 487.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a joint contribution from

Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Division of Farm Management and costs	C. L. HOLMES, *Principal Agricultural Economist, in Charge.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Cereal Crops and Diseases	M. A. MCCALL, *Principal Agronomist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - Price 5 cents

Technical Bulletin No. 346 March, 1933

THE EFFECT OF CONCENTRATION ON THE TOXICITY OF CHEMICALS TO LIVING ORGANISMS

BY

ERNEST BATEMAN

Senior Chemist, Forest Products Laboratory
Branch of Research, Forest Service

United States Department of Agriculture, Washington, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - Price 5 cents

TECHNICAL BULLETIN No. 346 MARCH, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

THE EFFECT OF CONCENTRATION ON THE TOXICITY OF CHEMICALS TO LIVING ORGANISMS

By ERNEST BATEMAN [1]

Senior Chemist, Forest Products Laboratory,[2] Branch of Research, Forest Service

CONTENTS

	Page
Introduction	1
The effect of the concentration of chemicals on the retardation of the growth of the wood-destroying fungus *Fomes annosus*	2
Method of conducting the tests	2
Petri-dish method	2
Flask method of testing toxicity	7
Calculation of experimental data	10
Mathematical discussion	17
Experimental results	19
Inorganic compounds	19
Organic chemicals	20
Discussion of experimental results	25
Conclusions from experimental work	26
Work of other investigators	26
Application of the analysis to data on bean aphis	27
Application of the analysis to data on the bacteria *Staphylococcus pyogenes aureus* and *Bacillus paratyphosus* and on anthrax spores	30
Work of other investigators—Continued	
Application of the analysis to data on green plants	32
Extension of the analysis to stimulation	33
Application of the hypothesis to *Bacterium coli*	37
Application of the hypothesis to the sprouting of wheat	37
Application of the hypothesis to growing peas	39
Application of the hypothesis to fungi	41
Application of the hypothesis to hydrogen ion	42
Discussion of the hypothesis	46
Application of the hypothesis to antagonism	48
Summary and conclusions	52
Literature cited	52

INTRODUCTION

The determination of the toxic effect of different chemicals upon living organisms is of interest to various groups of investigators. Consequently, the literature contains much information on the toxicity of various materials to animals and to plants.

It is the purpose of this bulletin to present a relationship between the concentration of a poison and its physiological effect upon a wood-destroying fungus and to point out that there seems to be a definite connection between the constitution of the chemical and the rate at which the toxic effect changes with changes in concentration. The relationship between the concentration and the physiological effect of a poison also appears to be applicable to aphids, to bacteria, and to green plants.

[1] This bulletin embodies the results of toxicity investigations made by the Forest Products Laboratory over a period of 10 years. It has been the author's privilege to draw without restraint upon the accumulation of information that has resulted from studies of toxicity by other members of the laboratory staff. The author wishes to acknowledge his indebtedness for the toxicity data to C. J. Humphrey, R. M. Fleming, and C. Audrey Richards of the Division of Forest Pathology, Bureau of Plant Industry, U. S. Department of Agriculture and particularly to C. H. Henningsen and R. H. Baechler, both of whom worked under the direction of the author at the laboratory.

[2] Maintained by the U. S. Department of Agriculture at Madison, Wis., in cooperation with the University of Wisconsin.

151455°—33——1

EFFECT OF THE CONCENTRATION OF CHEMICALS ON THE RETARDATION OF THE GROWTH OF THE WOOD-DESTROYING FUNGUS FOMES ANNOSUS

The work of other investigators on toxicity has well established the fact that as the concentration of a poison is increased, the effect on the organism in general becomes more marked (*1*, *4*).[3]

This bulletin attempts to show that the changes in toxic effect produced by changes in concentration can be stated mathematically. The data upon which this bulletin is based were collected in an investigation on the toxicity of various chemicals used as wood preservatives. A knowledge of the amount of chemical required to kill the organism would probably be most desirable; however, in a relative way, knowing the concentration at which the chemical prevents the growth of fungus, or the total inhibition point, is almost equally useful.

METHOD OF CONDUCTING THE TESTS

PETRI-DISH METHOD

The first part of the experimental work reported followed very closely the method of testing developed by Humphrey and Fleming (*7*) of the Division of Forest Pathology, Bureau of Plant Industry, Department of Agriculture, and modified by C. Audrey Richards of the same bureau. Richards (*13*, *p. 131*) describes the method as follows:

> Measured quantities of the hot filtered medium [which consisted of 25 grams Trommers' malt extract, 15 grams of bacto-agar dissolved in 1,000 c c of water] are poured into small bottles. Into similar bottles are weighed or measured amounts of preservative necessary to give the desired concentration. This concentration is based on the actual weight of the preservative in the final medium-preservative mixture. The bottles containing the proper amounts of preservative and medium are sealed, clamped into frames, and sterilized. The preservative and medium are kept separate until after sterilization in order to reduce the possibilities for chemical combinations. After sterilization the medium is poured into the preservative bottle under sterile conditions and the contents thoroughly mixed. In the case of water-soluble substances the mixture is easily obtained by shaking by hand, but in the case of oils it is necessary to use a specially designed motor-driven shaker. Just before the mixture reaches the temperature where the agar solidifies, it is poured into a sterile Petri-dish 100 mm in diameter and 15 mm deep. In using oily preservatives, when emulsions—not solutions—are obtained by the shaking process, the medium-preservative mixture is hardened immediately by placing the Petri-dish on ice. This quick cooling insures a uniform, finely divided emulsion.
>
> After the medium has cooled, a small piece of fungus cut from a vigorously growing Petri-dish culture is planted in the center of each dish. The inoculated dishes are then placed in an incubator and held at a constant temperature for from four to six weeks. Frequent growth readings are made.

The fungus used in the present work was a strain of *Fomes annosus* developed at the Division of Forest Pathology. It is exceptionally well fitted for this work because it is very resistant to the toxic action of chemicals, and it normally produces an easily measured growth in cultures. This strain has been adopted by the Division of Forest Pathology and others as the standard fungus for all toxicity testing for wood preservatives.

Falck (*3*) has shown that when the fungi *Merulius silvester*, *M. domesticus*, *M. sclerotiorum*, *Polyporus vaporarius spumarius*, *Verpa bohemica*, *Phycomyces nitens*, and *Mucor mucedo* are grown in a nutrient

[3] Italic numbers in parentheses refer to Literature Cited, p. 52.

agar-agar medium at constant temperature, the length of the mycelium is directly proportional to the age of the culture so long as the food and air supply are sufficient and other conditions remain constant.

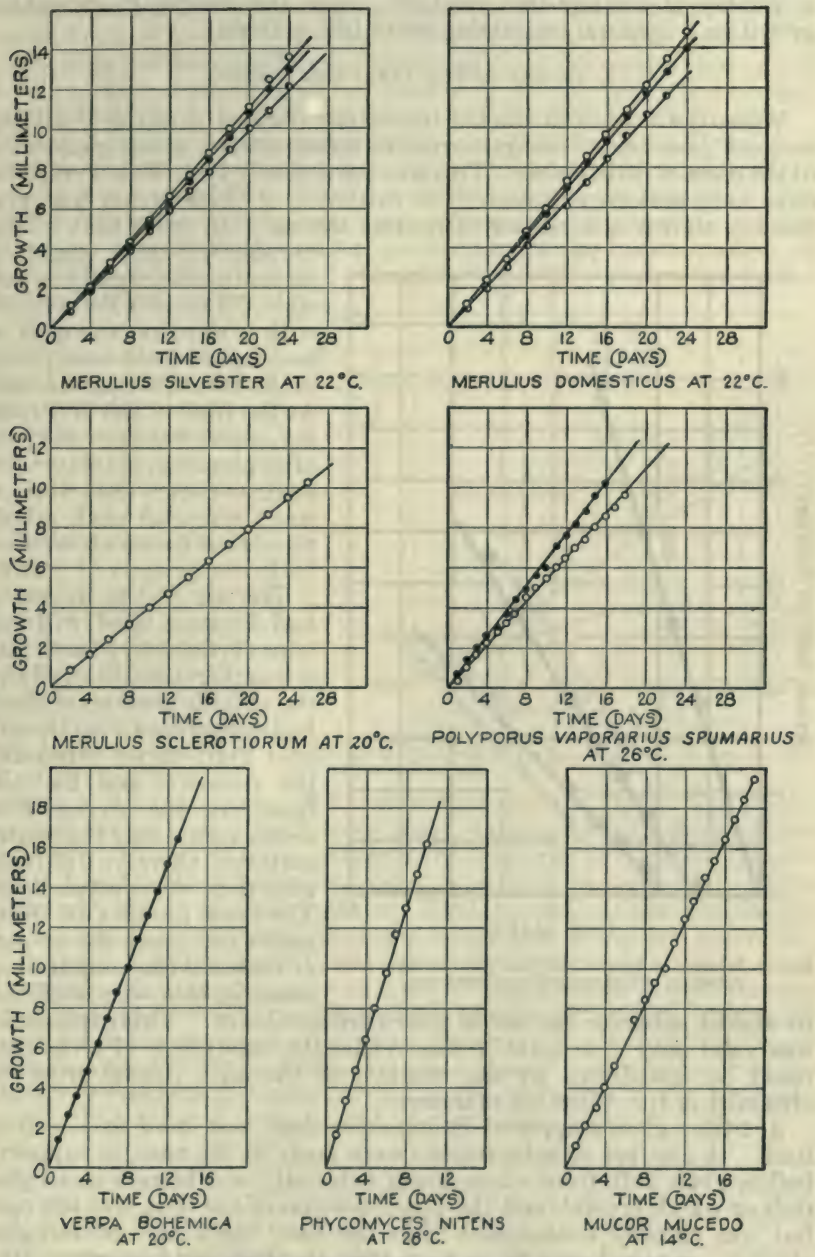


FIGURE 1.—Normal rate of growth of seven fungi. From data by Falck (3)

(Fig. 1.) The fungus *Fomes annosus* acts the same in this respect as those used by Falck. Furthermore, if the fungus is grown on an agar-agar medium containing a small quantity of a poison, the radial

growth of the fungus on a Petri dish will still be directly proportional to the time of growth, if the concentration of the poison is kept constant, although the rate of growth will be retarded. Figure 2 shows a number of straight-line relations when the fungus *F. annosus* is grown on a medium containing inhibiting material.

ERRORS IN THE PETRI-DISH METHOD

When the work was started it was not realized that the Petri-dish method gave rise to several errors in measurement which made some of the data of little value. This was particularly true of data collected over long periods of time. The existence of these errors was very forcibly shown in a matter of routine testing. In order that a large number of tests might be carried out as rapidly as possible, 75 or 100 Petri dishes with various amounts of coal-tar creosote were placed in the incubator at one time. At the time of the first reading, which was then one week after planting, the six or more control dishes that were always run with such a large number of dishes showed but little if any signs of growth.

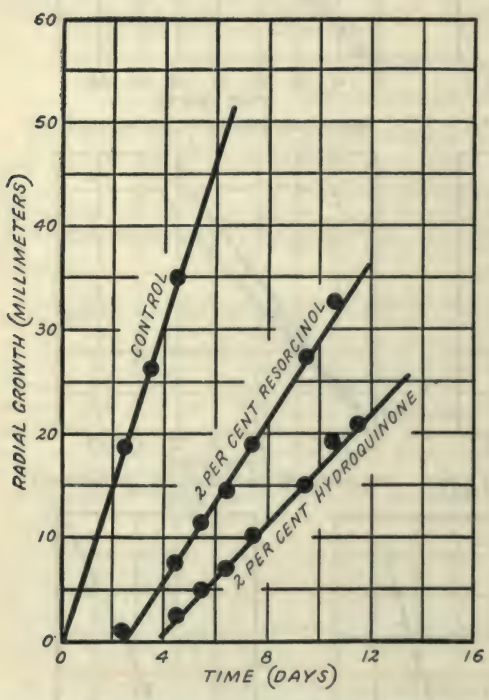


FIGURE 2.—Rate of growth of *Fomes annosus* on a non-poisonous and on two poisonous mediums

The air in the incubator had become filled with the odor of coal-tar creosote, and it was therefore believed that the volatile portions of the oil had evaporated from the covered Petri dishes containing the creosote, and had diffused into the covered Petri dishes containing the control cultures, thus inhibiting growth in the control dishes. The large number of dishes under test made the amount of material that might evaporate in this way sufficient to almost saturate the air in the entire incubator. This explanation was valid only if it could be shown that the toxic effect of a chemical could be transferred by the medium of the air. Actual proof was obtained in the following manner:

A 2-liter glass-stoppered Erlenmeyer flask was used as a culture flask. A number of indentations were made in the neck to support a hollow glass bulb from whose lower extremity was hung a small glass dish or watch crystal, and the upper portion of the bulb was left open but was entirely contained within the flask below the ground-glass stopper. Several such flasks were then sterilized, and approximately 150 g of sterile nutrient agar was placed within each. The agar was planted in the usual manner when it had cooled and solidified. Imme-

diately after planting, various toxic materials, such as phenol, cresol, naphthalene, and benzene, were placed on the watch glasses suspended at the top of the several flasks; none of the toxic materials could have reached the agar except through volatilization. In every case the predicted toxic effect was obtained. Furthermore, it was possible to obtain only partial retarding by using less than the quantity required to kill. These retarded growths differed in no way from the retarded growth obtained from nonvolatile compounds in solutions in agar.

Though the foregoing experiment showed that the closed Petri dish was not a suitable container for testing volatile compounds, it also pointed out a possibility of error with nonvolatile compounds. The medium in which all of the tests were made was chiefly water, a volatile material. Losses of the water would change the concentration of the toxic material and hence the rate of growth. Consequently the resulting growth plots, if taken over periods of from four to six weeks, should be curves and not straight lines. Moreover, the concentration at the end of the test might be different from the concentration upon which the test was started. An examination of the data available at that time showed that many of the plots were obtained over long periods of time; with nonvolatile compounds the curve was less steep at the end of the test than at the beginning, but with volatile compounds the reverse was true. Both facts are in conformity with the previous discussion. In a closed flask, however, the time-growth curves are practically straight lines within the experimental error of measurement. This is shown by Figure 3, which represents the data obtained simultaneously with a closed glass-stoppered flask and with a so-called closed Petri dish.

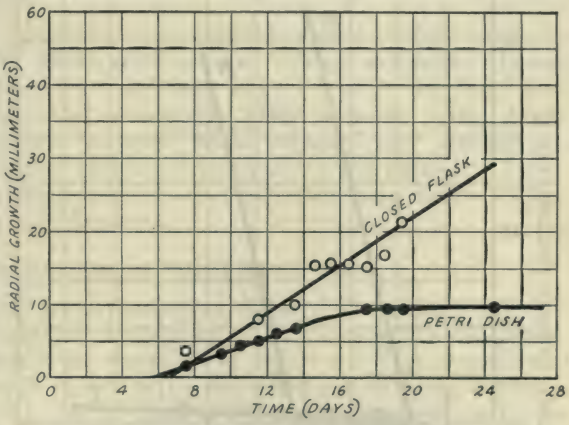


FIGURE 3.—Comparison between rate of growth of *Fomes annosus* on a medium containing hydroquinone solution in a closed flask and in a closed Petri dish

The loss of water from Petri dishes under test was of such vital importance that an attempt was made to gain a rough approximation of the amount lost. Three Petri dishes chosen at random were tared and the weights recorded after approximately 17 c c of nutrient agar had been added. These dishes were then placed in an incubator along with other material and weighed at the end of 11 and 24 days, respectively. The original weights and the losses are given in Table 1.

TABLE 1.—*Loss of water by evaporation from closed Petri dishes*

[Incubated at approximately 25° C.]

Original weight of agar	Loss at end of 11 days		Loss at end of 24 days	
Grams	*Grams*	*Per cent*	*Grams*	*Per cent*
17.85	5.62	32	11.12	62
18.03	2.32	13	6.16	34
18.55	6.94	37	11.71	63

There was considerable variation in the amount of water lost through evaporation, depending probably upon the tightness of the covers, but even the best result showed a loss in weight of 13 per cent in 11 days. Even with nonvolatile compounds an error of at least 10 per cent in the concentration would therefore be obtained at the end of 11 days. This loss was considered entirely too great for any but approximate determinations.

It was realized that with a more nearly airtight incubator the losses could have been greatly reduced, particularly if care had been taken to humidify the air in the incubator by the use of a relatively large dish containing water, but even then the Petri dishes could not be used with safety in working with volatile compounds. The Petri dish method was therefore discarded and a closed flask adopted instead.

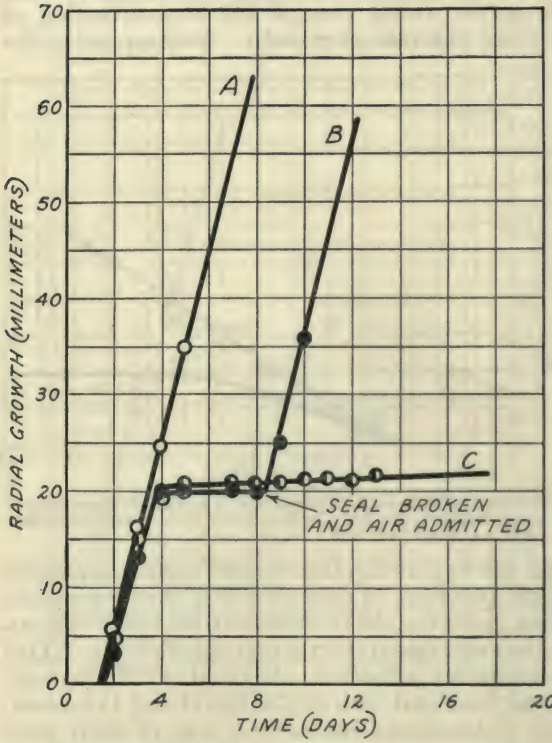


FIGURE 4.—Effect of lack of air on the rate of growth of *Fomes annosus:* A, Growth in unsealed Petri dish; B, growth in dish before and after breaking air seal; C, growth in covered dish with air-seal maintained

Perhaps the most important criticism that could be made of the use of a closed flask is that there might not be sufficient air to permit a steady normal growth of the organism. A few experiments were therefore made to determine the air requirement for the fungus.

The first of these consisted in selecting seven shallow Petri dishes of approximately 50 c c capacity. These were set with 17 c c of nutrient agar and planted in the usual way, but were sealed air-tight before being incubated. They were then incubated with three unsealed controls. Daily growth measurements were made on all the dishes at the same time. The results of three of these tests are shown diagrammatically in Figure 4; they show that air is an essential factor in toxicity testing. The largest Petri dish had a total capacity of 52.4 c c; subtracting from this the volume of the agar, or 17 c c, gives a total of 35 c c of air as being sufficient for only from two to three days' growth. One of the dishes was opened to determine if the rate of growth would remain the same after being retarded by lack of air. Curve B in Figure 4 shows that on the entrance of a new supply of air the rate of growth returned to normal.

The second experiment was carried out in large glass-stoppered, flat-bottomed weighing bottles having a total capacity of about 115 to 126 c c. The total air space in these bottles was reduced about 17 c c when the agar was inserted. The stoppers were sealed in, air-tight, after the agar had been inoculated. In every sealed bottle the growth at the end of three and one-half days exceeded the growth on the controls and had reached the edge of the dish so that no further measurements could be made. A maximum radius of 26 mm was obtained. On the supposition that the amount of air required is proportional to the area of the growth, it would appear that 400 c c of air should be more than is required for a growth equal to the radius of the flask. The ordinary wide-mouthed, 500 c c, glass-stoppered Erlenmeyer flasks fulfill the air requirement when 100 c c of agar are used. Flasks of this capacity or larger were used in the experiments here reported.

Some thought was given to replacing the glass-stoppered flasks by ordinary Erlenmeyer flasks with cork or rubber stoppers. It was shown that cork stoppers, even when covered with tin foil, were difficult both to sterilize and to keep in place without tying down. Rubber stoppers can not be used with volatile, oily compounds because of the absorption of the toxic material by the rubber. Moreover, they become hard with continued sterilization and nearly useless as stoppers after a few sterilizations.

FLASK METHOD OF TESTING TOXICITY

The method of testing finally adopted differed from the Petri-dish method only in replacing the Petri dish with glass-stoppered Erlenmeyer flasks with a minimum capacity of 500 c c. The quantity of agar used varied to some extent with the quantity of toxic material to be used; also with the size of flask, sufficient being used to insure nearly the same depth of agar in the center of the flask as was used in the Petri dishes. The detailed procedure was as follows.

The culture medium was prepared by heating with steam at atmospheric pressure for two hours a mixture of 1 liter of water, 15 g of Bacto agar, and 25 g of Trommer's malt sirup. After this mixture had been cooked it was filtered through cotton and measured quantities were poured into glass-stoppered Erlenmeyer flasks of 500 c c capacity. Usually 100 c c of agar was used in each flask. The quantity of agar was decreased when the material to be tested was available only in small quantities. When very low concentrations of a toxic material were to be tested the quantity of agar was increased; thus by increasing proportionately the quantity of toxic material used, the error of measurement was decreased.

The flasks containing the nutrient agar were stoppered with cotton plugs and the glass stoppers were covered with small pieces of cloth and fastened to the flasks during sterilization. The flasks were sterilized in an autoclave for 30 minutes at 15 pounds pressure. After sterilization a measured quantity of the toxic material was introduced either in the form of powder, liquid, or concentrated aqueous solution, depending on the nature of the toxic material. In many cases, particularly with sodium benzoate, it was impossible to introduce the toxic material as weighed powder because of contamination; a concentrated solution was found to be sterile. After the introduction of

the toxic material the glass stoppers were removed from their sterile cloth containers and placed in the flasks. The agar was then gently melted and the toxic material thoroughly incorporated by shaking. It was sometimes necessary to let the sterile agar stand two or three days to permit all parts of the agar to arrive at the same concentration; usually, however, the flasks stood overnight and were planted the next morning. The transplants, which were about 5 to 8 mm square, were taken from a culture of *Fomes annosus* that had been growing for from 5 to 12 days.

The concentrations used were recorded in percentage of the volume of agar taken because it was more convenient experimentally. When 100 c c of agar was taken, 1 g of toxic material equaled 1 per cent concentration, 1 mg of toxic material equaled 0.001 per cent concentration. For comparative purposes the molar basis is a better one to use. The experimental data have therefore been calculated to moles per liter by dividing the percentage concentration multiplied by 10 by the molecular weight of the compound under test.

DIFFICULTIES ENCOUNTERED WITH THE FLASK METHOD

While there are several minor difficulties, such as the darkening of the agar due to the interaction of the toxic materials and the fungus and the production of halos immediately beyond the growing fungus, only two seem worthy of discussion here and these only because they affect the values of the measurements. One of these difficulties was connected with the air requirement and occurred only in those flasks that contained easily oxidized materials, such as aniline or pyrogallol. In Figure 5 is a curve showing the growth on a solution of aniline. After nine days the growth of the fungus practically ceased, and no growth took place for nine days. A new supply of air was then admitted, and the growth started again at the original rate. The shape of the curve obtained here is almost identical with that shown in Figure 4, B, which was known to have been influenced by lack of air. In calculating the retarding effect on such curves the period of no growth was neglected.

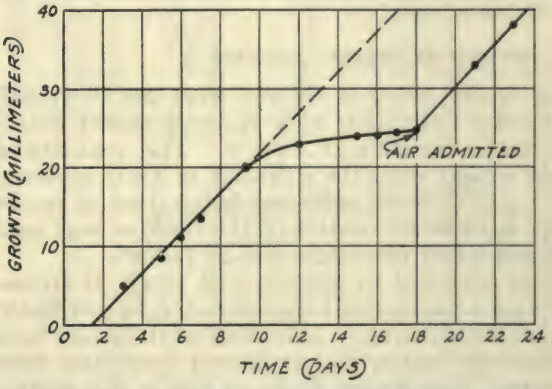


FIGURE 5.—Growth curves for *Fomes annosus* on a medium containing aniline solution showing rest period brought about by insufficiency of air

The other difficulty was encountered chiefly with oily toxic materials, such as benzene, chlorobenzene, or nitro compounds. With such materials, the surface of the transplant appeared at first to be of a gray slimy consistency; later this changed and the surface appeared like gray pebbly oilcloth. This condition often continued to the end of the test, but the transplant was not dead, because it recovered almost immediately on being transplanted to fresh, nontoxic agar.

Occasionally the transplant started to grow after long periods of no growth, and the growth continued at the same rate as that of a normal control culture. This rapid growth was even detected after 100 days of apparent inactivity. Under the microscope the fungous hyphæ appeared to divide into many smaller cells, each forming a chlamydospore. A few of these grew at the same rate as would be expected of the control. In one case, because a drop of condensed water ran down the side of the flask and over the transplant during the periodical examination, one of these sporelike bodies was carried away from the transplant so that it was possible to measure both the retarded growth

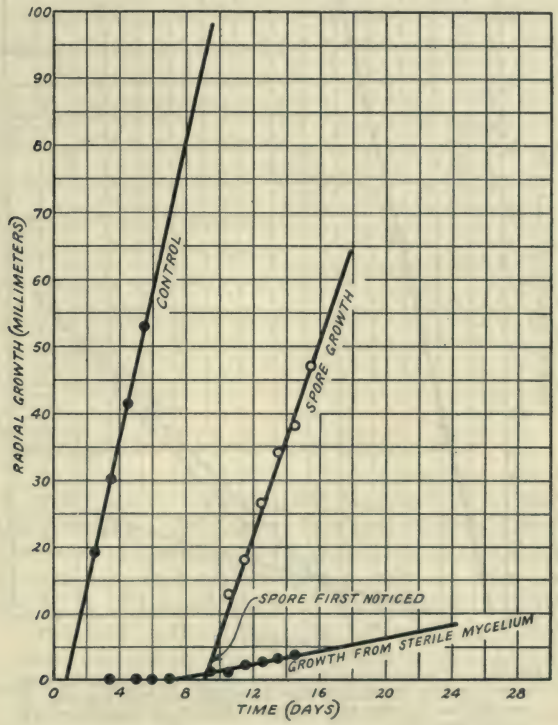


FIGURE 6.—Comparison of the rate of growth of a control with that of transplants originating from mycelium and from a spore

of the fungus and the rapid growth of the spore. These measurements are shown in Figure 6. In another case it was possible to detect the beginning of a spore growth by its luxuriant growth in the shape of a small pompom. Measurements were taken on both the retarded growth and the spore growth until the more rapid spore growth had entirely covered the slower retarded growth. These data are shown in Figure 7. If the two different growths had not been recorded in Figure 7, the curve would have resembled a steep curve such as might have been obtained if the loss of toxic material had been complete. While this apparent sporulation is of interest to the pathologist because it offers a possible explanation of the mechanism of accommodation, it is also of interest in the practical field of wood preservation

because it suggests that certain preservatives may appear to retard the growth, but if the organism is not killed there is always a chance of the formation of chlamydospores. It is evident that with such materials a different organism from the test organism, or at least a very different strain, must be considered. Whenever the growth was almost as rapid as the control, particularly if it followed a long inactive period, it was considered that a spore growth was responsible, and the particular test was repeated.

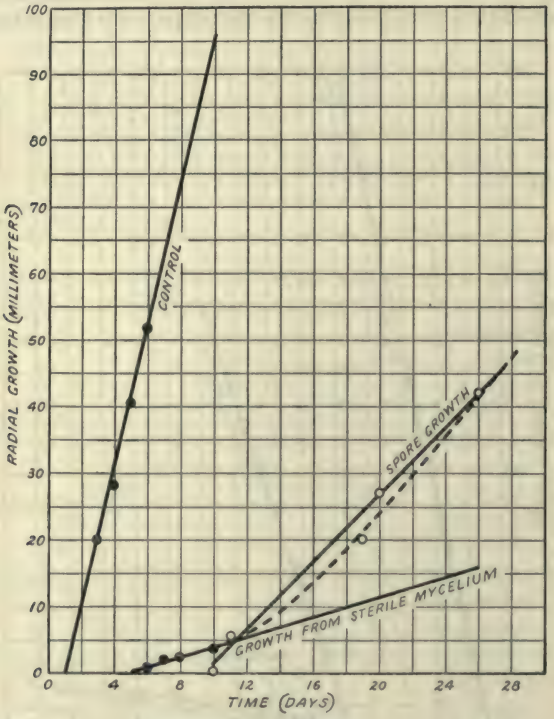


FIGURE 7.—Comparison of the rate of growth of a control with that of transplants originating from mycelium and from a spore. A combination of the two cultures yields a curve as shown by the broken line

CALCULATION OF EXPERIMENTAL DATA

When the radial growth of the fungus grown in closed flasks is plotted against the time of growth, a straight line is obtained at least within the limits of the radius of the containing flasks. Moreover, when the fungus is grown on agar containing a toxic material that retards the growth, straight lines representing time-growth curves are still obtained. This fact is illustrated in Figure 8. The chemicals represented in Figure 8, the exact composition of which is immaterial, have been introduced merely to illustrate the wide application of the straight-line relationship between growth and time when the cultures are grown in closed flasks.

The data obtained from the daily measurements of fungous growth are recorded in Table 2 and were later plotted on ordinary coordinate

paper along with the control. An almost ideal plot is shown in Figure 9 since all the growth lines appear to start at about the same time, but the growth is much slower than the control.

TABLE 2.—*Sample sheet showing method of recording data on the radial growth of Fomes annosus on a medium containing various concentrations of poison*

Time	Radial growth of *Fomes annosus* in a concentration of—						
	0 per cent [1]	0.02 per cent	0.03 per cent	0.04 per cent	0.05 per cent	0.06 per cent	0.07 per cent
Days	*Millimeters*	*Millimeters*	*Millimeters*	*Millimeters*	*Millimeters*	*Millimeters*	*Millimeters*
1							
2		2-2-2-2	1-1-1-1				
3	22-22-23-23			3-3-3-5	1-1-1-1	[2]	[3]
4	34-35-35-35	16-17-17-17	10-12-13-12			[2]	[3]
5	47-47-47-48			9-9-8-9	2-2-2-2	[2]	[3]
6	Covered.	28-29-29-29	17-18-17-17				
7				15-17-16-16	7-7-6-6		
8		Covered.	20-20-21-20	19-18-18-16	6-9-8-7	[2]	[3]
9				17-17-17-17	7-8-9-8		
10				20-22-20-23	10-11-11-10	[2]	[3]
11			32-32-33-32				
12				27-25-26-26	11-12-12-12		
13			36-38-38-39		11-15-13-12	[2]	[3]
14				30-30-30-30	15-15-15-15		
15						1-1-1-1	[3]
17					16-17-17-16	1-1-1-1	[3]
24						2-2-2-2	[3]
26						2-3-4-3	[3]
28						3-3-3-3	[3]
30							

[1] Control.
[2] Growth on transplant.
[3] Transplant white, no visible growth but no change to a slimy condition.

If the line in Figure 9 representing the growth of the control be extended until it reaches 100-mm radius and all the lines representing the retarded growth caused by the toxic action of the chemicals under test be read at this point on the time ordinate, the percentage of retarded growth is obtained without calculation. Subtracting the percentage of retarded growth from 100 per cent gives the percentage of retarding effect caused by the toxic action of the chemical. Either the percentage growth or the percentage of retardation provide a measure of the effect of the toxic chemical. The percentage of retardation gives values that are direct functions of the concentration and are easier to handle than the inverse functions of percentage growth. Throughout this work the percentage retardation has been used. The difference between the two systems of measurement is shown diagrammatically in Figure 10.

All of the data were not so ideal as that shown in Figure 9; in fact, the ideal condition of growth was obtained in only an occasional test. More commonly the retarded growths on the toxic solutions did not start immediately, because there was an initial rest period during which no growth was apparent. Even the control commonly took a day or more to get started. In some exceptional cases no growth was obtained on the control agar after two days and only slight growth at the end of three days, yet when the growth became established on the agar it continued as rapidly as if there had been no rest period.

It seems reasonable that the transplanting of agar containing the growing fungus from one position to another should cause a setback in the growth of the fungus. It also seems reasonable that if the

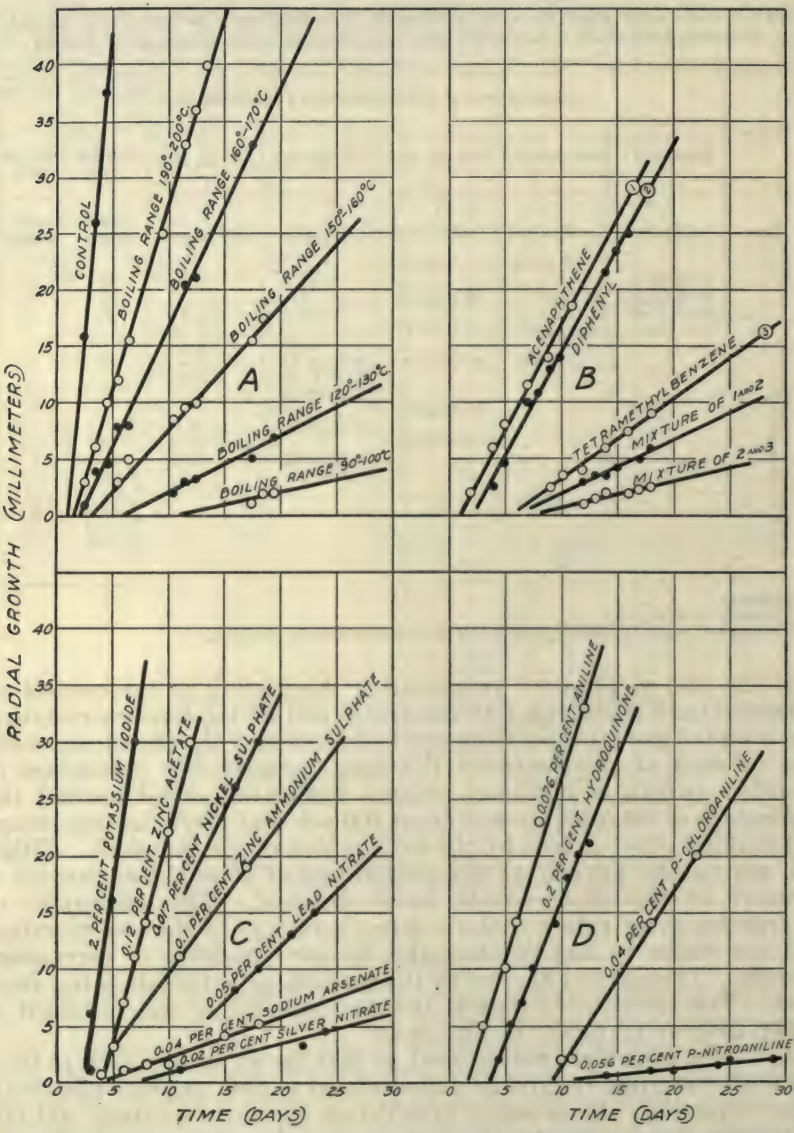


FIGURE 8.—Time-growth curves showing straight-line relation when *Fomes annosus* is grown on a medium containing toxic materials: A, Medium saturated with petroleum fractions; B, medium saturated with aromatic hydrocarbons; C, medium containing inorganic salts; D, medium containing organic compounds

transplant were placed on a medium on which it would have difficulty in maintaining itself that it would take a little longer time to become established. It might be suggested reasonably that this period of

delay in starting is a measure of the toxic effect of the medium upon which the fungus is trying to establish itself. If so, it is a very unreliable measure because the starting time varied over wide ranges even with the same concentration of the same toxic material. As shown in Figure 11, which diagrammatically presents the data for two identical concentrations of chloroaniline that were started at different periods of time, the starting time for one was 3 days and for the other 10 days. The controls for the two were duplicated, both as to starting time and rate of growth. For the present, therefore, the starting time must be looked upon, not as a measure of toxic effect, but as a rest or recovery period. The rate of growth on the toxic medium is a better measure of toxic effect. In Figure 11 the two lines representing the growth of the same concentration of chloroaniline but with different starting times, are parallel, indicating that the rate of growth is not affected by the rest period.

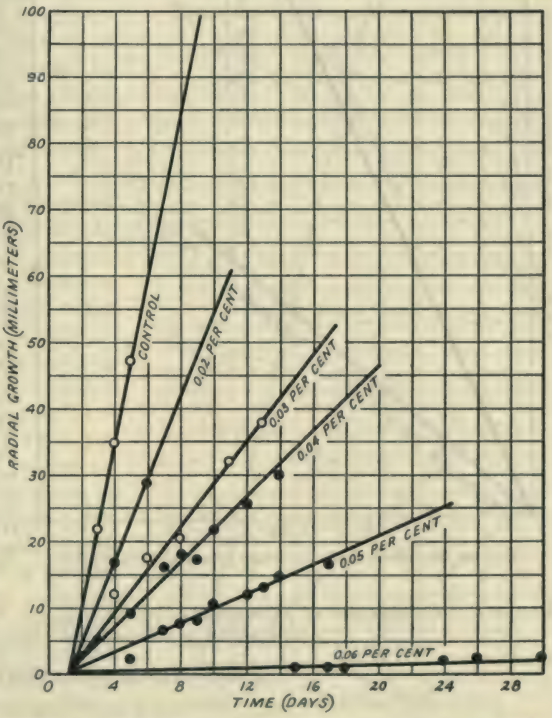


FIGURE 9.—Rate of growth of *Fomes annosus* on a medium containing different concentrations of *p*-nitroaniline

The simplest way of calculating the retarding effect, when the data contain rest periods, is to plot the data in the usual manner and obtain the best straight line through the data. Then draw a line parallel to this growth line in such a manner that the curve starts at the starting time for the control. From this corrected line the percentage retardation can be calculated in exactly the same way as it would be had the growth been ideal. Figure 12 shows the data collected on three concentrations of nitrobenzene and also the dotted lines which correct the data to ideal growth conditions. This method of plotting the data diminishes the experimental errors in two ways: (1) The plotting of the data to obtain the best straight line removes in large measure the errors caused by parallax and other difficulties in the actual measurement of the growth, and (2) the correction of this line to the ideal condition removes the error due to the resting period. The corrected data, therefore, give the most probable value for the percentage retardation and permit each concentration of toxic material to be represented by a single figure of the most probable percentage retardation.

The values obtained for the percentage retardation of the different concentrations of a single chemical were plotted against the various concentrations. In the resulting diagram the trend of the points may be along either a straight line or a curve, if ordinary coordinate paper is used, but conforms rather closely to a straight line on logarithmic paper if the logarithm of the percentage retardation is plotted against the logarithm of the concentration. The extension of the line to 100 per cent gives immediately the most probable total inhibition point, or the point at which no growth should be obtained. It also permits the data to be collected with a smaller number of tests, since each concentration serves as a check upon another concentration. The total inhibition point indicated by the extension of the line to 100 per cent can then be checked if more accurate figures are desired. For example, the data shown in Table 3 were obtained directly from the curves shown in Figure 9.

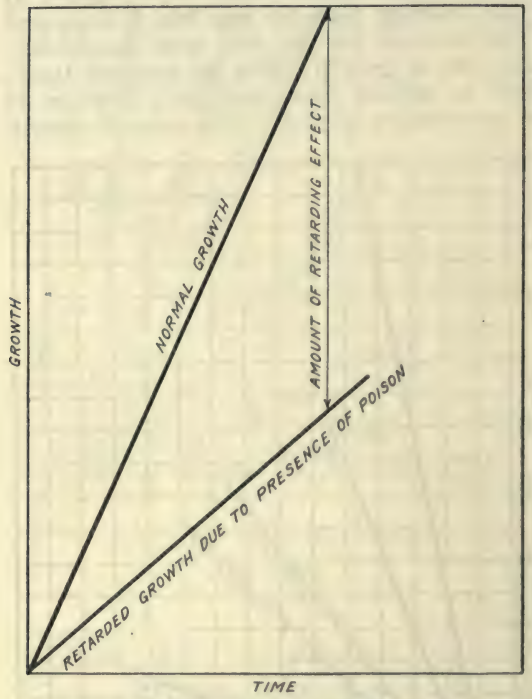


FIGURE 10.—Method of calculating percentage retardation

TABLE 3.—*Calculation of percentage of retardation for Fomes annosus on a medium containing p-nitroaniline solution*

[Data from the curves in Figure 9]

Concentration of *p*-nitroaniline	Growth obtained during same interval of time as was required for control to grow 100 mm in radius		Percentage retardation (100 per cent—per cent of retarded growth)	Concentration of *p*-nitroaniline	Growth obtained during same interval of time as was required for control to grow 100 mm in radius		Percentage retardation (100 per cent—per cent of retarded growth)
Per cent	*Mm*	*Per cent*	*Per cent*	*Per cent*	*Mm*	*Per cent*	*Per cent*
0.02	50.0	50.0	50.0	0.05	9.0	9.0	91.0
.03	26.0	26.0	74.0	.06	.7	.7	99.3
.04	19.5	19.5	80.5				

When the data in the first column were plotted on logarithmic paper against the data in the last column a straight line was drawn as shown in Figure 13.

DISCUSSION ON METHOD OF CALCULATING DATA

In general, the scheme of analysis and presentation of toxicity data used here depends upon two methods of plotting the results. These methods are (1) the plotting of the growth with time in such a manner that the effect of the different concentrations below the total inhibition point can be recorded in a numerical manner, and (2) the plotting of the numerical values for all the concentrations in such a manner that a straight line is obtained. The main objection to the method is that in general more labor is involved for an equal number of tests because greater attention must be given to those tests which are usually considered as negative. Aside from the fact that the data obtained seem to be of a more fundamental character, there are several other advantages in the scheme of analysis used here.

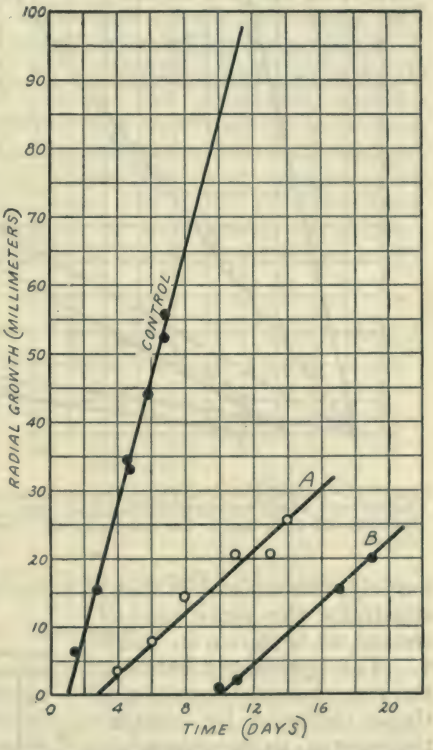


FIGURE 11.—Rate of growth of *Fomes annosus* on a medium containing *p*-chloroaniline solution of the same concentrations: A, Started growing 3 days after transplanting; B, started growing 10 days after transplanting

(1) A more effective control of the experimental conditions is made possible while the experiments are in progress, because experience has shown that such major variations from straight-line growth curves as are shown in Figure 5 are due to changes in concentration of the toxic material; these occur either because of evaporation of the water or the chemical itself, or because of the chemical action of the toxic material. In many such cases the concentration after a period of time is not the same as when the test was started. Experience has also shown that when curves are obtained which show little or no growth for quite a period, followed by a growth almost as rapid as that of the normal culture, it is almost always because of the production of spores from which, apparently, a more resistant strain of fungus is obtained.

(2) A smaller number of check tests are necessary because the method of plotting makes each concentration serve as a check on all other concentrations.

(3) Since the method requires the recording of the effect of concentration below the total inhibition point in a numerical manner, it permits the calculation of the effect of a combination of two or more toxic materials which by themselves are insufficiently soluble totally to inhibit growth. This use is best illustrated by Figure 8, B, which shows the growth curves for saturated solutions of diphenyl

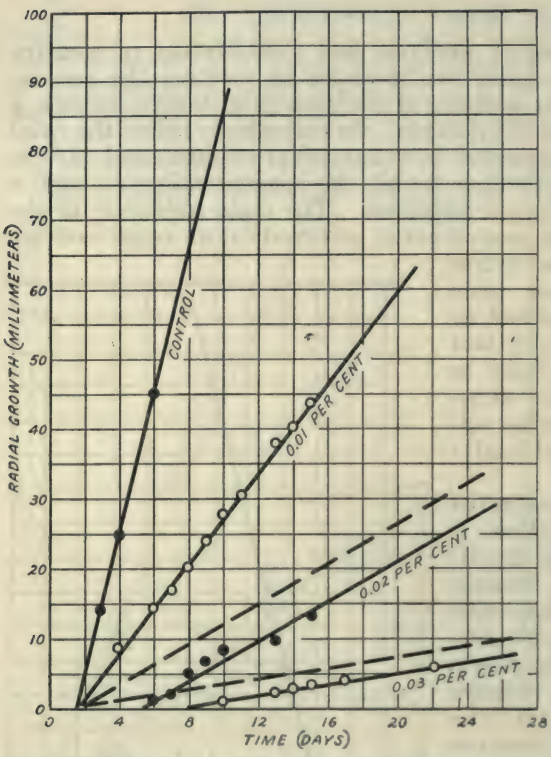


FIGURE 12.—Rate of growth of *Fomes annosus* on mediums containing different concentrations of nitrobenzene. Solid line represents experimental data; broken line represents data corrected for rest periods

and acenaphthene and for a saturated mixture of the two in the same test. The percentage retardation for acenaphthene as given in the footnote to Table 4 is 82.6 per cent; for diphenyl 84 per cent. If the two compounds reacted independently of each other, it would be expected that the growth permitted under their combined effect would be the product of the respective retarded growths produced by their use, because the retarded growth with the first chemical becomes the equivalent of the normal growth as far as the second chemical is concerned. Therefore, the combined effect should be 0.174×0.160, or 0.028, or 2.8 per cent, or a retardation of 97.2 per cent. Two other pairs of compounds, namely, durene and diphenyl, and durene and acenaphthene, gave substantially the same kind of results, as is shown in Table 4. The agreement between the experimental results and those obtained by calculation seems to be somewhat better than fortuitous. If this is the proper way of calculating the effect of saturated solutions of more than one compound, none of which is alone able completely to inhibit the growth of the fungus, this leads to the conclusion that, from a theoretical point of view, no combination of such compounds would ever be able completely to inhibit the growth of the fungus, although it might very

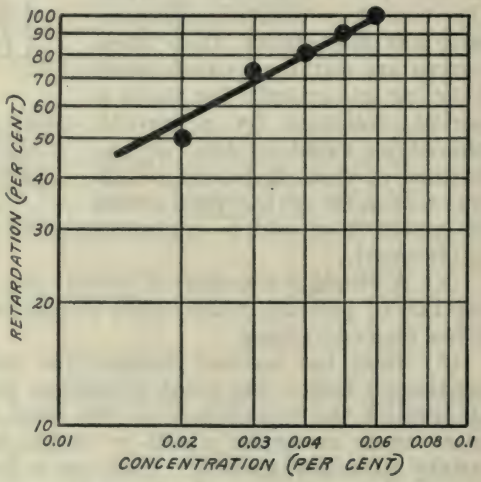


FIGURE 13.—Example of plotting percentage retardation against concentration

seriously retard it. This idea was tested by combining diphenyl, durene, and acenaphthene. The combined calculated effect should be a percentage retardation of 99.88 per cent, or a growth of 1½ mm in 100 days. At the end of 21 days no visible growth was noticed, but the fungus was not dead, because by merely aerating the flask to remove the hydrocarbon the vitality of the fungus was restored, and at the end of the third day after aeration started it was apparently making the same rate of growth as that on the unpoisoned medium. These calculations make it appear probable that when saturated solutions of materials, none of which is by itself soluble enough to exert a full lethal effect, are combined, the combined effect of two or more can be calculated from the individual results, provided the solubility of none of the materials has been affected by the presence of the others. The calculation raises a very interesting point as to what would be the effect of two or more soluble toxic materials administered in doses which, if each material were taken alone, would be insufficient to kill the organism. It also raises the question whether or not a similar mode of action may be expected in a solution containing toxic basic ions, toxic acid ions, and toxic undissociated molecules. Should such a relationship, or one based on similar principles, occur, it would aid materially in the work on mixed toxic materials.

TABLE 4.—*Comparison of calculated and experimental results when saturated solutions of two hydrocarbons, neither of which is lethal, are used*

Mixture contains—	Calculated retardation [1]	Observed retardation
	Per cent	*Per cent*
Acenapthene and diphenyl	97.2	96.6
Acenapthene and durene	99.2	98.8
Diphenyl and durene	99.3	99.4

[1] Percentage retardations of saturated solutions of each alone are: Acenapthene, 82.6 per cent; diphenyl 84 per cent; and durene, 95.6 per cent.

MATHEMATICAL DISCUSSION

In order that the succeeding discussion may be understood more easily, it seems desirable to give a short discussion at this point of the mathematics involved in the experimental work. Since it has been shown that within the limits of the experimental work the radial growth of the fungus can be represented by a straight line on ordinary plotting paper, the relation between radial growth and time can be expressed by the general equation of a straight line, or $G=K\ (t-m)$, in which G is the radial growth, K the slope of the line, t the time, and m the rest period that occurs before the fungus grows. The method of comparing the different rates of growth eliminates m as being of no consequence in this connection. The equation can therefore be written:

$$G=Kt \text{ or } K=\frac{G}{t}$$

where t is the time elapsing after the rate of growth has become established.

K the slope represents the rate of growth of the fungus in the particular experiment. In order to compare the rate of a retarded growth with the rate of the normal growth, the slope for the retarded growth has been expressed as a percentage of the slope for the normal growth; that is,

K retarded growth $=K$ normal growth times the percentage of retarded growth

This procedure gives inverse functions of the concentration; that is, as the concentration increases, the values of K normal growth times the percentage of retarded growth decrease. This was obviated by subtracting the percentage growth from 100 and calling the result the percentage retardation, or R. The actual growth in millimeters per day on any toxic solution is therefore expressed as

$$K_{\text{normal growth}}\left(1.00-\frac{R}{100}\right)=\frac{G}{t}$$

When the values of R were plotted against the concentration on logarithmic paper the data conformed closely to a straight line; that is,

$$\log R=\log D+n \log C$$

in which R is percentage retardation, C the concentration of the toxic material, log D a constant, and n the slope of the line. The normal form of this equation is

$$R=DC^n$$

which is the general equation of a parabola.[4] The straight line shown in Figure 13 therefore represents a parabola, and the relation between percentage retardation and concentration is a parabolic relation. The values of C, the concentration, may be expressed in terms of percentage concentration or in terms of moles per liter without changing the value of the slope, but the value of the constant D will be changed by a value that depends on the n^{th} power of the ratio between the values in percentage concentration and moles per liter.

In the growth equation

$$K_{\text{normal growth}}\ (1.00-R)=\frac{1}{t}\ G$$

R can therefore be replaced by DC^n to form the equation

$$K_m\ (1.00-DC^n)=\frac{1}{t}\ G$$

When the values of K_m, the normal growth, and D, C, and n are known, the effect of any concentration within the limits of the parabolic relation can be calculated and should reproduce the actual experimental figures corrected for the rest period.

[4] Parabola or parabolic curve as used in this bulletin refers to any of the curves represented by the general equation $y=ax^n$, where n is positive, and not with the restricted meaning where $y=ax^2$.

EXPERIMENTAL RESULTS

When the percentage retardation for the various toxic materials was plotted against the concentration as given in the preceding discussion, the straight lines on logarithmic paper had a number of different slopes. It was first thought that the slopes of the various lines were of little or no consequence but that they were characteristic of the individual chemical. It was found, however, that as the data accumulated there were several groups whose slopes were nearly the same, that the average of these would portray the data fully as accurately as the experimental work justified, and that in each group there existed a similarity of chemical construction that did not seem to be entirely fortuitous. The six following figures show the concentration-retardation curves for these groups of chemicals. Within each group the line representing the change in percentage retardation with changes in concentration is parallel to the other lines in the same group and interprets the data within the limits of the experimental error of the methods used.

INORGANIC COMPOUNDS

The inorganic compounds naturally divide themselves into two groups: (1) Those chemicals whose basic radicals, such as silver, mercury, and copper, can be considered as the toxic radical, and (2) those compounds whose acid radicals, such as arsenate and tungstate, may be considered as the toxic radical. In general, the salts are preferred for this type of work because they eliminate the effect of the hydrogen or hydroxyl ions. Growth of the fungus *Fomes annosus* has been obtained on approximately half-molar solutions of sodium chloride, potassium chloride, magnesium sulphate, and calcium acetate; none of these radicals can be considered as very toxic.

Figure 14 gives the data collected from inorganic salts whose basic radicals may be considered as toxic, and Figure 15 gives the similar data collected from inorganic salts whose acid radicals may be considered as toxic. Tables 5 and 6 give the total inhibition points as determined by extending the percentage retardation-concentration curves to 100 per cent (p. 20).

TABLE 5.—*The most probable total inhibition points of salts in which the basic radical is poisonous*

Salt	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total inhibition point	Salt	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total inhibition point
	Mole per liter	*Mole per liter*	*Mole per liter*		*Mole per liter*	*Mole per liter*	*Mole per liter*
Nickel sulphate	0.00092	0.0015	0.00115	Silver nitrate	0.00132	0.00153	0.00137
Nickel ammonium sulphate	.0012	.00172	.00140	Copper chloride	.0017	.0023	.00182
Mercuric chloride	.00017	.00021	.00022	Uranium acetate	.0024	.0028	.00272
Thallous sulphate	.0004	.00058	.00047	Cadmium sulphate	.0057	.0036	.0066
				Zinc acetate	.011	.0165	.0143

TABLE 6.—*The most probable total inhibition points of salts in which the acid radical is poisonous*

Salt	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total inhibition point	Salt	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total inhibition point
	Mole per liter	*Mole per liter*	*Mole per liter*		*Mole per liter*	*Mole per liter*	*Mole per liter*
Sodium arsenite	0.002	0.0025	0.0025	Sodium tungstate	0.0235	0.067	0.067
Sodium arsenate	.0028	.0039	.0039	Ammonium molybdate	.33	.39	.39
Sodium chromate	.0013	.0030	.0015				

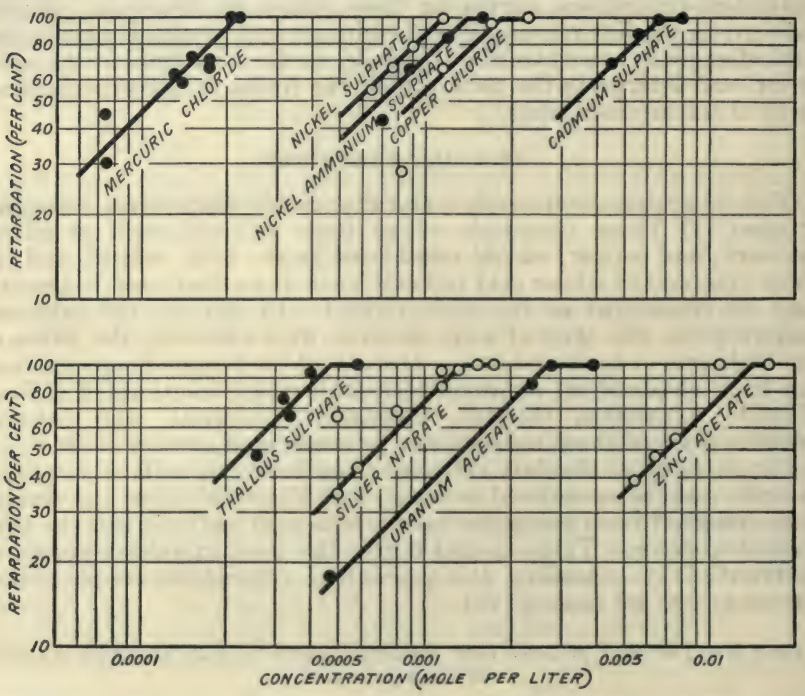


FIGURE 14.—Concentration-retardation curves for inorganic materials with poisonous basic radicals against the fungus *Fomes annosus*

It is evident that the slopes of lines given in Figures 14 and 15 are quite different. Lines with a slope that seems to fit the acid radicals can not be drawn through the points representing the data for basic radicals, or conversely.

ORGANIC CHEMICALS

Very little if any data are available on the toxicity of aliphatic compounds; most of the work has been confined to the aromatics, chiefly benzene derivatives. The benzene derivatives present a number of possible combinations having different structures. The disubstituted compounds are perhaps better suited to show the effect of differences in structure than any other class because many disubstituted compounds can be obtained that have the same substituent

groups in different positions. It would be expected that the greatest difference would be obtained by comparing the ortho with the para disubstituted compounds since these present the greatest structural differences.

Figure 16 presents the data obtained with para substituted benzene derivatives. Figure 17 gives similar data obtained with ortho substituted benzene derivatives. Tables 7 and 8 give the total inhibition points of these compounds as determined graphically. The lines representing the data for the ortho compounds can not be made to represent the para compounds, or conversely. This difference in behavior can only be explained by the difference in structure since the two groups of compounds contain the following structural isomers: *p*-chlorophenol, *p*-aminophenol, *p*-nitrophenol, *p*-chloroaniline, *o*-chlorophenol, *o*-aminophenol, *o*-nitrophenol, and *o*-chloroaniline.

FIGURE 15.—Concentration-retardation curves for inorganic materials with poisonous acid radicals against the fungus *Fomes annosus*

TABLE 7.—*The most probable total inhibition points of para substituted benzene derivatives*

Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition point	Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition point
	Mole per liter	*Mole per liter*	*Mole per liter*		*Mole per liter*	*Mole per liter*	*Mole per liter*
p-chlorophenol	0.00125	0.00145	0.0013	*p*-chloroaniline	0.0032	0.0039	0.0039
p-nitrophenol	----------	.00107	.0009	*p*-nitroaniline	.0044	.0046	.0046
p-aminophenol	.0275	.036	.031	Hydroquinone	.036	.045	.039

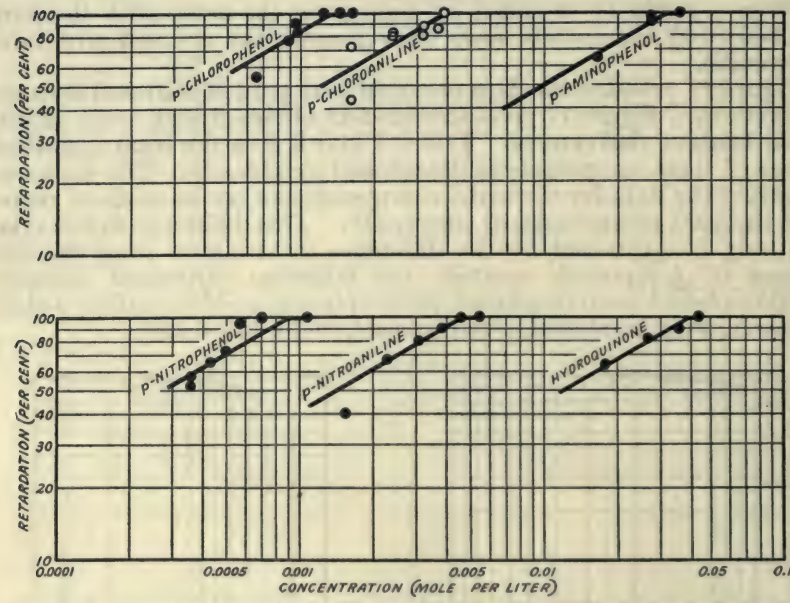


FIGURE 16.—Concentration-retardation curves for para substituted benzene derivatives against the fungus *Fomes annosus*

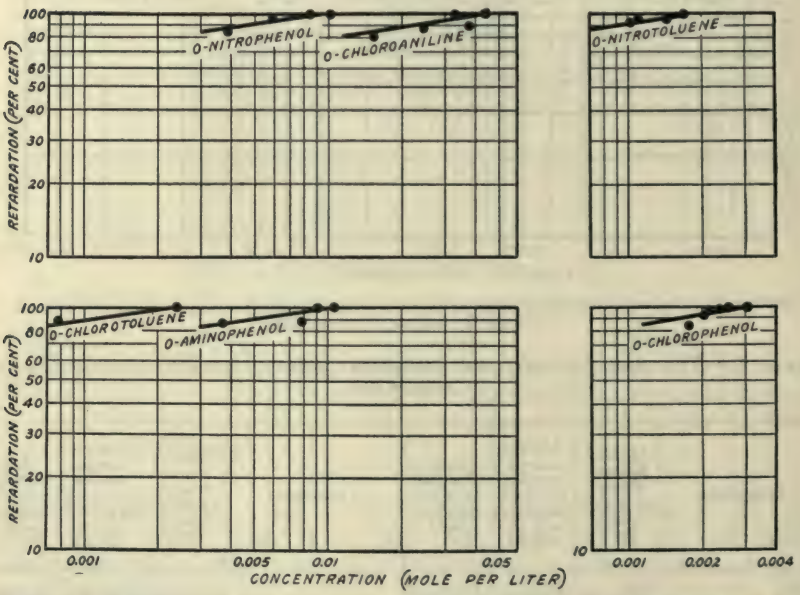


FIGURE 17.—Concentration-retardation curves for ortho substituted benzene derivatives against the fungus *Fomes annosus*

TABLE 8.—*The most probable total inhibition points of ortho substituted benzene derivatives*

Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition point	Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition point
	Mole per liter	*Mole per liter*	*Mole per liter*		*Mole per liter*	*Mole per liter*	*Mole per liter*
o-chlorotoluene	0.00078	0.0024	0.0024	o-nitrotoluene	0.00145	0.0017	0.0017
o-nitrophenol	.00084	.0014	.0009	o-aminophenol	.0092	.0108	.0105
o-chlorophenol	.0026	.0031	.0031	o-chloroaniline	.0038	.0044	.0044

There was one major exception to the behavior of ortho and para substituted compounds. This occurred in the salts of the substituted benzoic acids. Before these can be discussed it is necessary to present the data for the monosubstituted derivatives of benzene shown in Figure 18.

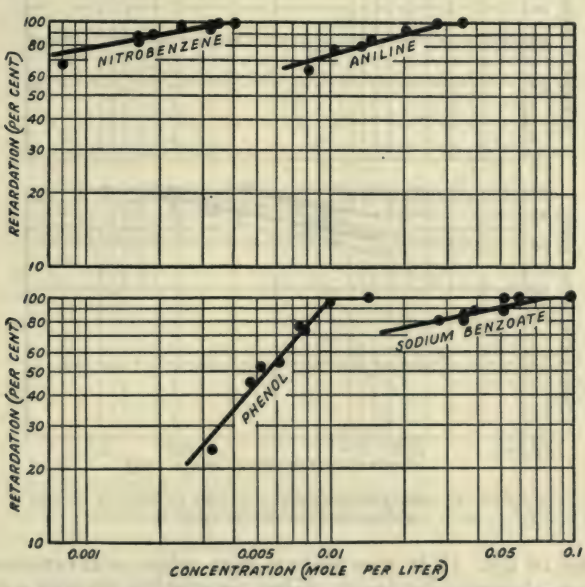


FIGURE 18.—Concentration-retardation curves for monosubstituted benzene derivatives against the fungus *Fomes annosus*

The total-inhibition points are given in Table 9. In the monosubstituted compounds there seems to be no general slope that will fit all the data; the structure of the four monosubstituted derivatives may be represented as follows:

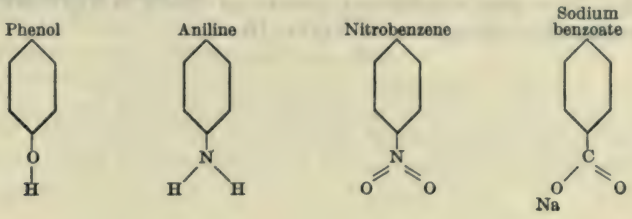


TABLE 9.—*The most probable total-inhibition points for monosubstituted benzene derivatives*

Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition point	Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition point
	Mole per liter	*Mole per liter*	*Mole per liter*		*Mole per liter*	*Mole per liter*	*Mole per liter*
Sodium benzoate	0.06	0.098	0.08	Phenol	0.01	0.0145	0.0102
Aniline	.028	.035	.03	Nitrobenzene	.0041	[1]	.0042

[1] No normal growth was obtained at 0.0044 and 0.0054 mole per liter, but abnormal spore growth was obtained. At 0.0065 mole per liter no growth of any kind was obtained, and the fungus was dead.

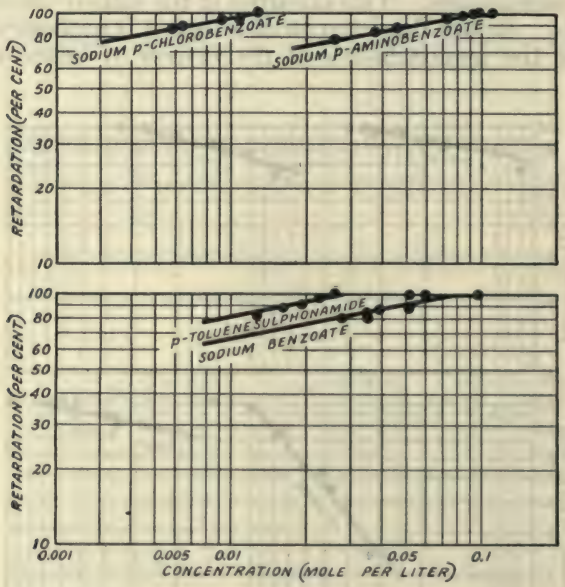


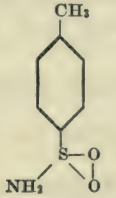
FIGURE 19.—Concentration-retardation curves for salts of benzoic and substituted benzoic acids

In Figures 16 and 17 it was shown that when combinations of any two of amino, chlorine, hydroxy, nitro, or methyl groups were present in the same molecule the slope of the line representing the effect of concentration on the percentage retardation seemed to be dependent upon the relative positions of the two groups. This was not so with the sodium salts of substituted benzoic acids, the slopes of which were more nearly parallel to the slope of sodium benzoate as shown by Figure 19. The total-inhibition points of these compounds, determined graphically, are given in Table 10.

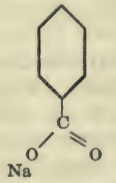
TABLE 10.—*The most probable total inhibition points of the salts of benzoic and substituted benzoic acids*

Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition points	Compound	Highest concentration at which fungus grew	Lowest concentration at which no growth was obtained	Most probable total-inhibition points
	Mole per liter	*Mole per liter*	*Mole per liter*		*Mole per liter*	*Mole per liter*	*Mole per liter*
Sodium benzoate	0.06	0.098	0.082	Sodium *p*-chlorobenzoate	0.011	0.0128	0.0128
Sodium *p*-aminobenzoate	.1	.11	.11	*p*-toluenesulphamide	.026	--------	.030
Sodium *m*-aminobenzoate	.084	.094	.094				

Another exception is *p*-toluenesulphonamide. This may be looked upon as the ammonium salt of *p*-toluenesulphonic acid from which one molecule of water has been lost. Its structure may be represented by:



which is very similar to that of sodium benzoate:



P-toluenesulphonamide has a physiological action very similar to that of sodium benzoate, suggesting that all the sulphonic acid salts may behave in a very similar manner.

DISCUSSION OF EXPERIMENTAL RESULTS

The departures of several of the points in Figures 14 to 19 from the lines averaging the series to which the points respectively belong are somewhat greater than can be attributed to experimental error. Most of these points occur at the lower concentrations. This seems to indicate that in such materials the effect of low concentrations is quite different from that of high concentrations in the rate at which the toxic effect increases with concentration.

Whatever may be the cause of this apparent change in behavior, it is sufficient here to limit the discussion to the region over which the parabolic relationship shown by the experimental work holds good. At present these limits appear to be as follows: Between 60 and 100

per cent retardation for para compounds, or when the slope of the toxicity concentration curve is 0.56; between 80 and 100 per cent retardation for ortho compounds, or when the slope is 0.15; between 80 and 100 per cent retardation for substituted benzoic acids, or when the slope is 0.19; between 20 and 100 per cent retardation for inorganic basic radicals, or when the slope is 1; and between 90 and 100 per cent retardation for inorganic acid radicals, or when the slope is 0.07. When stated in terms of concentration, the relationship seems to hold in all compounds between the concentrations producing total inhibition and a concentration only one-third as great.

The straight lines shown in the logarithmic plots, such as in Figures 14 to 19, are equivalent to parabolic or simple-power curves on ordinary cross-section paper. The equation of such a curve may be written $R=DC^n$ in which R is the percentage retardation and C is the concentration. The exponent n is the slope of the line on logarithmic paper, and D is a constant or parameter whose value depends on the position of this line. The experimental work indicates that one value of n is applicable to a group of chemicals of similar constitution. It may, therefore, be considered that n is determined by the structure, or configuration, and D by the composition of the chemical.

CONCLUSIONS FROM EXPERIMENTAL WORK

The following conclusions can be drawn from the experimental work on *Fomes annosus:*

The radial growth of the fungus *Fomes annosus* is directly proportional to the time of growth, provided other conditions are the same.

There is a definite relationship between the concentration and the percentage retardation of the growth of *Fomes annosus* grown on nutrient agar containing various chemicals.

This relationship may be expressed as a straight line on logarithmic paper and holds true apparently between the total inhibition point and approximately one-third of that concentration. For this portion a parabolic relation apparently exists.

It is possible to arrange chemicals in groups whose percentage retardation-concentration curves are similar in slope and in which the chemical constitution is also similar.

The relationship between concentration and percentage retardation may be expressed by the general equation

$$R=DC^n$$

in which R is the percentage retardation, C the concentration, n a constant or exponent which seems to be a function of the chemical structure, and D a constant which seems to be dependent upon the individual compound.

WORK OF OTHER INVESTIGATORS

A comprehensive search of all the literature to find whether similar relationships exist in other organisms is well-nigh impossible and has not been attempted. In fact, only a small portion of the literature has been reviewed and even a smaller portion of that reviewed has been used. It is believed, however, that the data presented in this

critical review are sufficient to show the possibility of a wider application of the scheme of analysis used here and to aid in the development or extension of relationships which were beyond the scope of the original data. In dealing with different organisms, different methods of measuring toxicity must be used. In general, the toxicity is measured by whatever convenient measure is available. If the toxicity data are of such a nature that they can be put into terms comparable with the percentage retardation of the previous discussion, it is possible to determine whether a similar relationship exists between toxic effect and concentration. Arranging chemicals in groups of like constitution and like rate of change in toxic action with changes in concentration is a more difficult task, because it requires a sufficient number of chemicals of like constitution to establish the best relationship, and also because there is no reason to believe that the relationship shown in the experimental work on fungi would hold in exactly the same manner with other organisms. In fact, it would be surprising if this were true, but some other arrangement of like chemicals in groups showing, in general, the same sort of influence, though with different numerical value, would not be surprising. But, as stated previously, a sufficient number of tests would be required to establish the relationship. Such data are not likely to be found in the literature unless some other investigator has proceeded along a similar line of attack as that followed in this bulletin.

In attempting to find the relationship in toxicity data with other organisms, cognizance must be taken of the fact that in some toxicity work the organisms normally live beyond the length of the experiment, while in other work the organisms normally die under the conditions of the test, even if no toxic agent is present.

APPLICATION OF THE ANALYSIS TO DATA ON BEAN APHIS

Tattersfield, Gimingham, and their coworkers have conducted extensive toxicity tests (*15*, *16*, *17*) using insects and worms as their organisms. Since such organisms are representatives of the animal kingdom whereas the wood-destroying fungus *Fomes annosus* represents the vegetable kingdom, the data are of particular interest because any scheme of analysis that can be used on the toxicity data from two such widely separated groups must approach the fundamentals of toxicity as a whole. Many of the data collected on the bean aphis (*Aphis rumicis*) by these workers are not susceptible to the mathematical treatment proposed here because, for the most part, they record only the lethal concentration and give no idea of the relative effect of concentrations below lethal doses. Tattersfield, Gimingham, and Morris report experiments (*16*, *p. 220*) on more than 60 organic compounds with approximately 10 aphids for each compound. The accidental death of two aphids would, of course, introduce a large error in their data. This is perhaps the reason why the authors state:

> It should be pointed out that the curves on the diagrams are not suitable for mathematical analysis and can not be used for exact interpolation; they are intended to show the general trend of the experimentally determined points * * *.

The relationship between toxic action and concentration under the scheme of analysis used here does not require the exact determination of the killing point, but does require that a sufficient number of deter-

minations be made below the killing point so that the trend of the effect of the concentration can be determined.

As much of Tattersfield's data as possible has been taken, keeping in mind that the data can not be more accurate than 10 per cent and that a 20 per cent error would probably be within the limit of the occasional experimental error. Tattersfield's data give both the number of survivors and the number dead or dying. The number dead when expressed on a percentage basis is similar to the percentage retardation, if it can be assumed that the weak aphids die at lower concentrations than the stronger ones. The method of plotting also

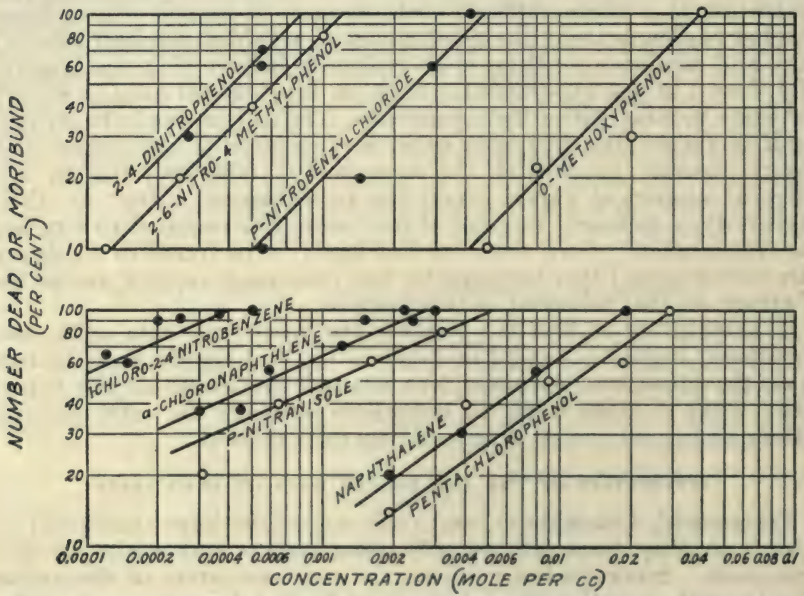


FIGURE 20.—Concentration-death curves for various chemicals against the bean aphis (*Aphis rumicis*). From data by Tattersfield, Gimingham, and Morris (*16*)

requires that at least three determinations be recorded below the concentration that was lethal to all the subjects investigated. This condition is fulfilled by only 13 of the pure organic materials used by Tattersfield. The curves for 9 of the 13 materials are given in Figure 20. The others have been omitted for the sake of clearness of the figures. Only four of the points shown in Figure 20 are farther away from the lines drawn than would be accounted for by the death of one aphid. Two of the four points in the curve are for *o*-methoxyphenol. The actual record taken from the original paper and the number of deaths required by the curve for this chemical are shown in Table 11. The best agreement is furnished by 2-6 nitro- 4 methylphenol, which gives a straight line including all four points.

TABLE 11.—*Comparison between the number of deaths obtained by experiment* [1] *and that required by the curve for o-methoxyphenol*

Concentration	Number unaffected	Number dead	Required by curve	Difference
Mole per 100 c c				
0.0403	0	10	10.0	0.0
.0201	7	3	4.7	1.7
.008	7	2	1.7	.3
.004	9	1	1.0	.0
[2].002	8	2	.5	1.5

[1] From data by Tattersfield, Gimingham, and Morris (*16*).
[2] This point not plotted in Figure 20.

The data furnished by Tattersfield and his coworkers on the toxicity of the alkaloids (*16*) also plot as straight lines on logarithmic paper. (Fig. 21.) Their data on the toxic effect of various plant

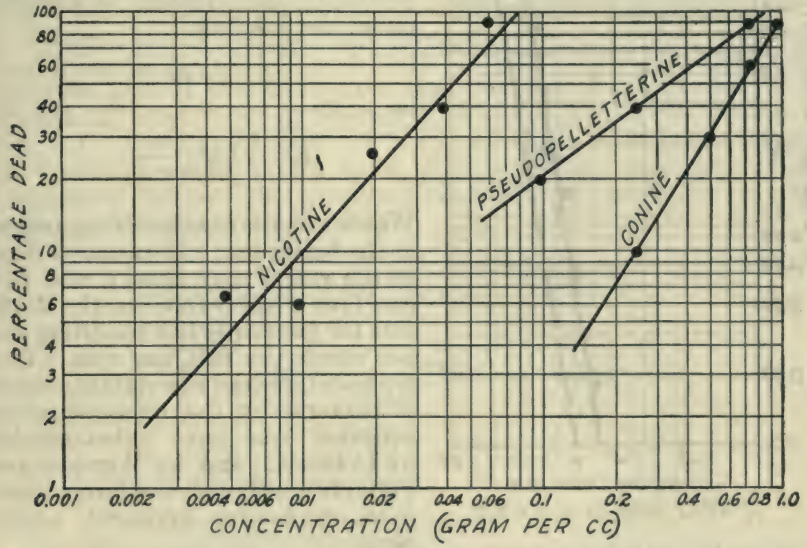


FIGURE 21.—Concentration-death curves of alkaloids against the bean aphis (*Aphis rumicis*). From data by Tattersfield, Gimingham, and Morris (*16*)

extracts, and the like, need not be considered here because the extracts were necessarily impure toxic substances. These are outside of the scope of the present discussion since their consideration necessarily leads to a discussion of the complex relationship that must exist when two or more dissimilar toxic materials are mixed together or when a water-soluble toxic material is dissolved in an oil.

Of the 9 curves shown in Figure 20, 1 is the hydrocarbon naphthalene, 1 is an alpha substituted naphthalene, 1 is an ortho substituted benzene, 2 are para substituted benzenes, 2 are trisubstituted benzenes, 1 a tetrasubstituted benzene, and 1 a hexasubstituted benzene. In view of the meagerness of the data it is not possible to arrange the compounds into groups of like or nearly like constitution. It is believed, however, that there is sufficient evidence to show that the parabolic relationship between changes in concentration and toxic effect holds here as with fungi.

APPLICATION OF THE ANALYSIS TO DATA ON THE BACTERIA STAPHYLOCOCCUS PYOGENES AUREUS AND BACILLUS PARATYPHOSUS AND ON ANTHRAX SPORES

The conditions of many toxicity tests in which bacteria are used as test organisms are such that the bacteria would slowly die without the aid of the toxic material. The effect of the toxic material is therefore to increase the death rate. It is essential to know something about the death rate under the conditions of the tests before any attempt is made to determine whether or not the parabolic relationship between concentration and toxic effect holds with bacteria also.

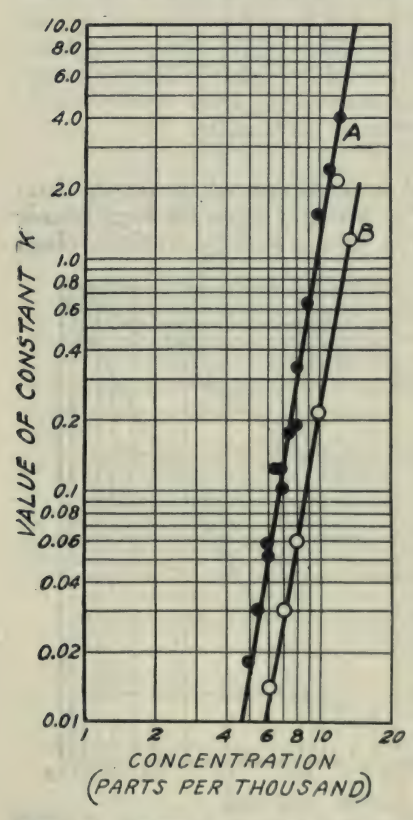


FIGURE 22.—Changes in the value of the constant K with changes in concentration of the disinfectant (phenol). A, against the bacterium, *Bacillus paratyphosus;* B, against the bacterium, *Staphylococcus pyogenes aureus.* From data by Chick (*1*). The data for A are calculated to the logarithm base e, while those for B are calculated to the base 10. This avoids interference of one curve with the other. The data for B can be converted to the base e by multiplying by 2.30

Chick (*1*), following the suggestion given by Krönig and Paul (*9*), found that the viability curve of bacteria can, in general, be represented by the equation of a monomolecular reaction,

$$a-x=ae^{-Kt}$$

or

$$K=\frac{1}{t}\log\frac{a}{a-x}$$

Where a is the number of organisms at the beginning; x the number dead at the end of any time, t; and K a constant which expresses the death rate for the particular condition under which the test was run. This representation of the viability curve of bacteria by the monomolecular equation was later substantiated by Cohen (*2*) and by Winslow and Falk (*18*), although the latter paper notes numerous apparent exceptions.

Any change in the conditions of the test changes the value of the constant K since it changes the rate of death. The constant K of those conditions must, therefore, contain the factor K_1 for the normal death rate and P for the percentage effect of the poison. This part of the equation could therefore be written

$$K=K_1\ (1.00+P)$$

or

$$K=K_1+K_1P$$

If K_1 were known, it would be very simple to calculate the values of P and the experimental value of K, but Chick does not give any

value from which K_1 could be calculated. If, however, the value of K_1 is small in comparison to the values of K_1P it can be neglected and therefore K can be taken as equal to K_1P. Since P is comparable to percentage retardation, the value of K should plot as a straight line on logarithmic paper, because the multiplication of P by any other constant will not change the slope of the parabola that might be formed by the various values of P obtained from different concentrations.

Chick, working with *Bacillus paratyphosus* and *Staphylococcus pyogenes aureus* tested the toxic action of phenol against these organisms. She presented evidence to show that the monomolecular-reaction equation could be modified to fit the various conditions of her experiments. It is not the purpose here to question the validity of Chick's modified equation, but merely to point out that the relationship shown in the experimental part of this bulletin also fits the data. To this end the values of the constant K for each concentration of phenol have been worked from Chick's original data as given in Tables 12 and 13, and plotted against their concentration, the assumption being that K_1 was small. Part of these data are shown in Figure 22. It is evident from the steepness of the line in Figure 22 that K_1 must be small because K equals K_1+K_1P has a value of only 0.01 at a concentration of 4, and at a concentration of 2 parts per thousand would have a value of 0.001. They show a parabolic relationship between the concentration and the value of the constant as is required by the relationship.

TABLE 12.—*Time required for killing 30,000,000 Staphylococcus pyogenes aureus at 20° C. with varying concentrations of phenol* [1]

Phenol parts per 1,000 (C)	Time taken for disinfection (t)		Phenol parts per 1,000 (C)	Time taken for disinfection (t)	
	Hours	*Minutes*		*Hours*	*Minutes*
14.0	0	4.5	7.0	3	6.0
12.5	0	2.5	6.0	6	35.0
10.0	0	25.0	[2] 4.0	23	42.0
8.0	1	35.0			

[1] From data by Chick (*1*).
[2] This point not plotted. It is slightly above the curve.

TABLE 13.—*Time required for reduction in number of about 30,000,000 Bacillus paratyphosus at 20° C. to less than 60 with varying concentrations of phenol* [1]

Phenol parts per 1,000 (C)	Time taken for disinfection (t)		Phenol parts per 1,000 (C)	Time taken for disinfection (t)	
	Hours	*Minutes*		*Hours*	*Minutes*
12.0	0	3.25	[2] 3.0	75	0
11.0	0	5.5	8.0	0	45.0
10.0	0	8.5	7.5	1	15.0
9.0	0	20.5	7.0	1	45.0
8.0	1	8.0	6.5	2	5.0
7.0	2	6.0	6.0	3	45.0
6.0	4	0	5.5	7	20.0
[2] 4.5	19	0	5.0	11	30.0
[2] 4.0	19	0			

[1] From data by Chick (*1*).
[2] These points not plotted. The point for 4.5 parts of phenol is on the line; the other 2 are slightly above.

Chick also reproduces the data of Krönig and Paul on the effect of mercuric chloride on anthrax spores. These data have been handled in a manner similar to that described for Chick's data. The values of the constants K for Krönig and Paul's data are plotted against their concentrations in Figure 23.

From these data it appears more than likely that the parabolic relationship shown in the experimental work on fungi can be used with satisfactory results when bacteria are the test organisms. The complete equation for the viability of bacteria may therefore be written as

$$DC^n = \frac{1}{t} \log \frac{a}{a-x}$$

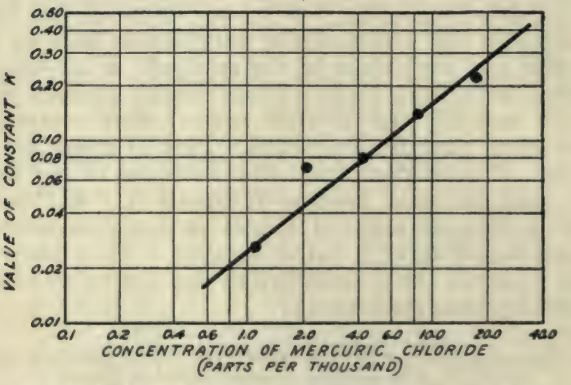


FIGURE 23.—Changes in the value of the constant K with changes in concentration of mercuric chloride against anthrax spores. From data by Krönig and Paul (*9*)

where DC^n is equal to P if the normal viability constant is small, and as

$$K_1 (1.00 + DC^n) = \frac{1}{t} \log \frac{a}{a-x}$$

if the normal viability constant K_1 is large in respect to DC^n.

This last form is similar to the equation of growth for fungi as given on page 18.

$$K_m (1.00 - DC^n) = \frac{1}{t} G$$

The left side of the equation, which is the side governing the rate, differs only in the sign. The viability curve for the fungus was a life curve and was opposed by the toxic action; the viability curve of the bacteria was a death curve and was aided by the toxic action.

APPLICATION OF THE ANALYSIS TO DATA ON GREEN PLANTS

The effect of different materials upon growing plants has long been of interest to mankind because the whole science of fertilizers is bound up with the effects of lime, magnesia, ammonia, and the like, upon growing plants. These effects are of particular interest to those plants commonly used as foods. McCool (*12*) measured the effect of various poisons on peas and wheat, grown in distilled water,

Pfeffer's nutrient solution composed entirely of inorganic salts in distilled water, and in soil. He measured the weight of the green tops, the weight of the green roots, and the average length of both roots and tops. Because of the wide range of the investigations and because in many cases mixtures of two bases were used, not all of his data were valuable for use here.

Figure 24, which has been plotted from McCool's data, shows the effect of increasing the concentration of manganese chloride on the weight of the tops of peas grown in nutrient solution. The data are given in Table 14.

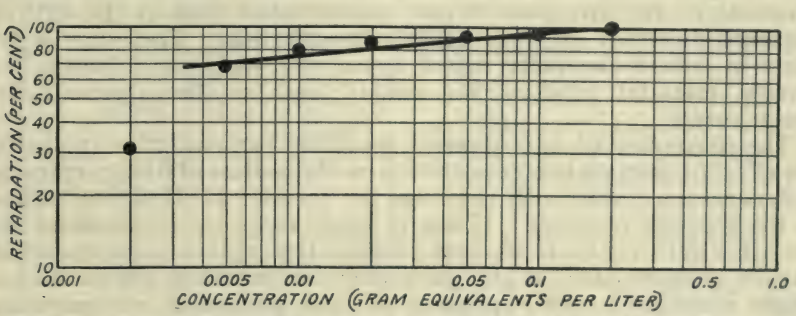


FIGURE 24.—Concentration-retardation curves for manganese chloride against Canada field peas grown in nutrient solution. From data by McCool (*12*)

TABLE 14.—*Effect of manganese chloride on the weight of tops of peas*

Concentration of manganese chloride	Weight of green tops [1]	Retardation		Concentration of manganese chloride	Weight of green tops [1]	Retardation	
N	*Grams*	*Grams*	*Per cent*	*N*	*Grams*	*Grams*	*Per cent*
0 [2]	10.40	0	0	0.020	1.50	8.90	85.6
.002	7.20	3.20	30.8	.050	.85	9.55	91.0
.005	3.20	7.20	69.2	.100	.64	9.76	94.0
.010	2.20	8.20	78.8	.200	.00	10.40	100.0

[1] From data by McCool (*12*). [2] Nutrient solution.

The parabolic relationship given on page 18 expresses the data from the total inhibition point to approximately one-fifteenth of that concentration as accurately as the experimental data will allow. The effect of changing the concentration of the posion shown here has also been confirmed in other examples on green plants. The toxic effect can therefore be considered as a parabolic function of the concentration of the poison for a very considerable part of the range.

EXTENSION OF THE ANALYSIS TO STIMULATION

A discussion on the general effect of changes in the concentration of a toxic material can not well be concluded without some consideration of the stimulating effect of low concentrations. This is particularly true here, where it has been shown that an increase in concentration causes an increase in toxic effect and that within certain limits the increase in toxic effect appears to be a simple parabolic function of the concentration. Since a parabolic function does not

permit of any reversal in the curve, no stimulation can be accounted for by this simple parabolic function. However, the fact that poisonous materials when used in low concentrations frequently act as stimulants is well known. Winslow and Falk (*18*) ascribe to Richet the discovery that there are certain concentrations of the same salts which are (1) indifferent, (2) stimulating, (3) inhibitive, and (4) toxic. Winslow and Falk point out that the change from a stimulating to a retarding influence is apparently a continuous process and that the influence can be represented by smooth curves. It is extremely difficult for the chemist to visualize a single reaction that proceeds in one direction at one concentration and in the entirely opposite direction at some other concentration. There are a few cases in colloid chemistry where apparently one concentration of a foreign material peptizes the colloid and another concentration coagulates it.

The conception of two opposed reactions can easily be applied to the effect of changes in concentration on the welfare of living organisms if it is assumed that both reactions are present at all concentrations of the reacting material. If one of these reactions is beneficial and the other detrimental to the well-being of the organism, the one which has the greatest effect at any particular concentration will be the one whose influence is more apparent at that particular concentration. If the two reactions are equal at some concentration, there will be no apparent effect. This bulletin has shown that the detrimental effect of a poison on a fungus, on aphids, on bacteria, and on green plants is very closely approximated by a parabolic function of the concentration, at least within the range of the data shown.

If this range is extended into the region where stimulation is obtained the whole range of change in concentration can be represented by two parabolas, one representing a detrimental and the other a beneficial effect. At no concentration can either effect be measured alone, because of the presence of the other opposing effect. The measurable results are the net resultant of these two opposed reactions. When the beneficial reaction is greater than the detrimental reaction the net result will be stimulation. When the detrimental reaction is greater than the beneficial reaction the net result will be a toxic action. At the point at which the two are equal there will be no measurable effect. The net stimulation must be added to the figure representing the growth of the organism in the absence of the chemical under investigation, and the net detrimental effect must be subtracted from this figure. When the net detrimental effect equals the normal growth, no growth or total inhibition is obtained. The measurable detrimental effect can not therefore exceed the normal growth, but the net stimulation may exceed the normal growth. No such limitations apply to either effect if taken by itself; the detrimental effect, if taken by itself, may be many times the normal growth provided it is opposed by a beneficial effect which is great enough to bring the difference between the two effects within the range of measurement. Since the beneficial and detrimental reactions have different rates, the curves representing their plotting on logarithmic paper must cross.

Some explanation is necessary, since a hypothesis is now offered which proposes to represent by the difference between two crossed parabolas the same effect that was previously represented by a single

parabola. Fortunately, this conception of two crossed parabolas is the explanation of the exceptions and discrepancies noted in the early part of the bulletin. Figure 25 shows three different pairs of crossed parabolas representing beneficial and detrimental reactions. The difference between the two is the net beneficial and net detrimental effect. In these figures the net beneficial effect, or stimulation, is always on the left side of the crossing point of the two lines. This is added to the normal growth. The net detrimental effect is always on the right side of the crossing point. It must be subtracted from

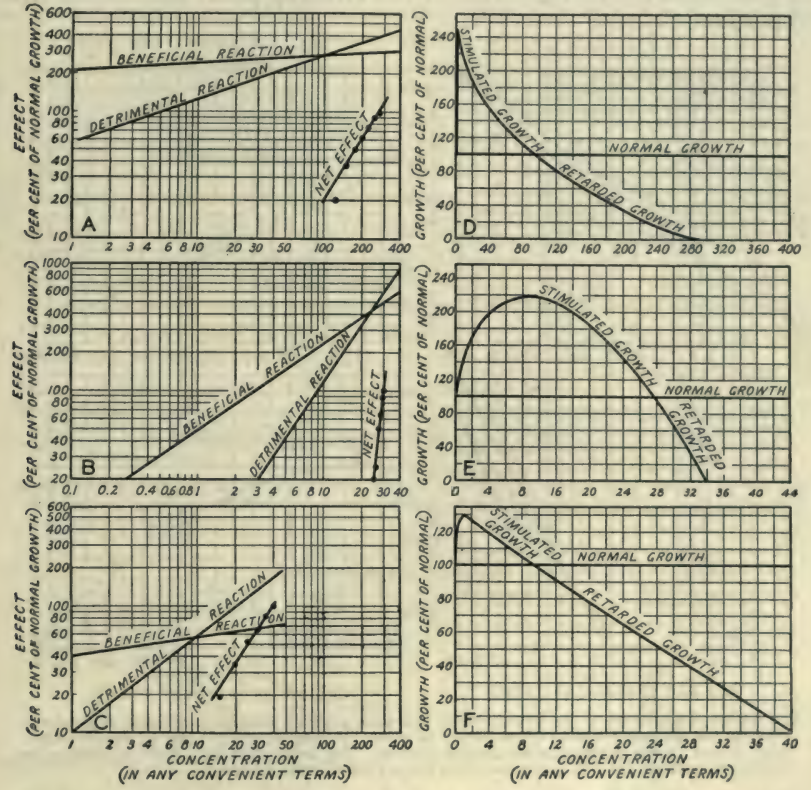


FIGURE 25.—Illustration of the hypothesis of beneficial and detrimental effects used as parabolic functions of the concentration: A, B, and C, crossed parabolas; D, E, and F, the corresponding growth curves. The heavy line with dots represents the difference between the two parabolas when the net effect is detrimental

the normal growth. The net detrimental effect obtained by these pairs of crossed parabolas is shown by the heavy line with dots in Figure 25. Any investigator collecting data within the range of toxic effect would be justified in drawing a straight line through the experimentally determined points represented by the dots because the differences of the experimental data are less than 5 per cent from the line, and are within the limit of error of most experimental toxicity data. A close examination of the points in Figure 25 shows that the data are not true straight lines but are curves and that the points have a tendency to be above the line in the center and below the line at both ends. In experimentally determined points the experimental

error may throw the point on either side of the line, and a straight line relation would be even more justified.

In order that the idea of crossed parabolas may be more clearly depicted the curves in Figure 25, A, B, and C, have been replotted on ordinary coordinate paper as total growth lines. (Fig. 25, D, E, and F.) The normal growth is represented by a horizontal line drawn at 100 per cent. The portion above this line is the difference between the two parabolas at the left side of the crossing point added to 100 per cent. The portion below this line is the difference between the two parabolas at the right side of the crossing point subtracted from 100 per cent.

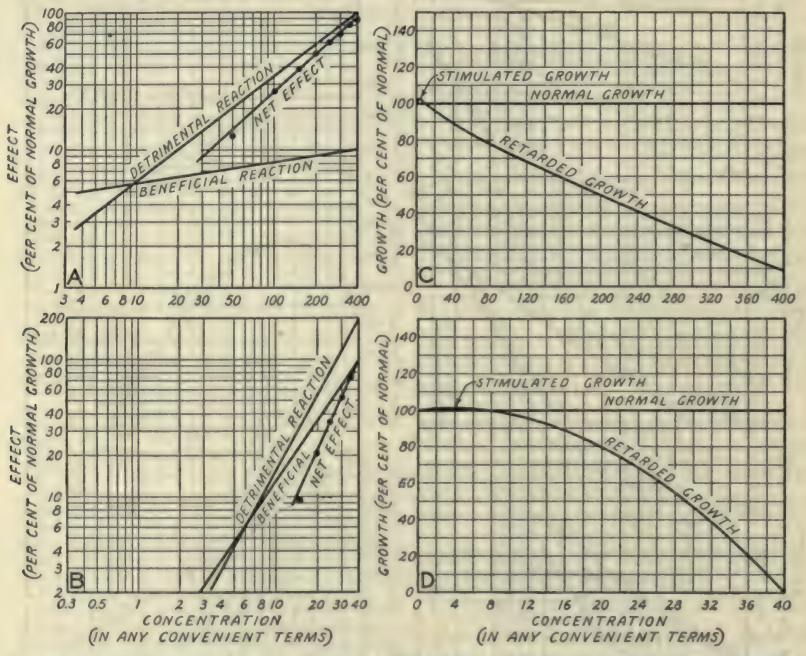


FIGURE 26.—Illustration of the hypothesis of beneficial and detrimental effects used as parabolic functions of the concentration when there is no measurable stimulation: A and B, crossed parabolas; C and D, the corresponding growth curves. The heavy line with dots represents the difference between the two parabolas when the net effect is detrimental

One objection to the hypothesis of crossed parabolas is that some organisms do not show a net stimulation with certain chemicals; others may not show a stimulation with any materials even when the whole range is carefully investigated. In Figure 26, curves A and B show two pairs of crossed parabolas representing opposed beneficial and detrimental effects. The growth curves for the crossed parabolas in Figure 26 are shown opposite them in C and D. Both pairs of curves show a stimulation which is less than the experimental error and would ordinarily be missed or considered as erroneous. In Figure 26, D, this condition exists for over one-fourth the distance between zero concentration and the total inhibition point. The objection that no stimulation can be shown, therefore, does not eliminate the possibility that the net effect can be depicted by crossed parabolas. Curve C of Figure 25 showing stimulation and curve A of

Figure 26 showing no measurable stimulation are made up of two pairs of crossed parabolas having the same slopes, but different intercepts. The point of crossing in curve C is at concentration 9.5 and percentage effect 56; in curve A the parabolas cross at concentration 9.5 and percentage effect 5.6.

APPLICATION OF THE HYPOTHESIS TO BACTERIUM COLI

The data presented by Hotchkiss (*6*) afford an excellent opportunity of testing out the hypothesis of two reactions with *Bacterium coli*. Hotchkiss measured the effect of a number of cations on the number of bacteria present at stated intervals. For the most part her data show only the numbers present at one time during the test. The time of the test is, therefore, of no interest in this connection, provided that the same interval is used for each concentration. For convenience, her data have been recalculated into percentage of the normal numbers alive as indicated by the control cultures that were run at the same time. When the percentage alive exceeds 100 per cent of the normal, the stimulating effect was greater than the detrimental effect and, conversely, when the percentage alive was less than 100, the detrimental effect was the greater.

There is at present no simple way of calculating the real values of the beneficial and detrimental reactions from data as collected. It is, however, very simple to pick out by "cut and try" methods a pair of parabolas that will fit the data for each compound.

Some of the data collected by Hotchkiss (*6*) have been so plotted and the results of this method of "calculation" are shown in Table 15 along with the original data recalculated to percentage effect.

TABLE 15.—*Comparison between the calculated and experimental values of the effect of various concentrations of inorganic salts on the viability of Bacterium coli*

Salts	Concentration	Number surviving after 9 hours		Salts	Concentration	Number surviving after 9 hours	
		Calculated	Observed[1]			Calculated	Observed[1]
	Mole per liter	*Per cent*	*Per cent*		*Mole per liter*	*Per cent*	*Per cent*
Magnesium chloride	0.0125	148	147	Zinc chloride	0.000001	146	139
	.025	160	160		.000005	136	139
	.050	172	190		.00001	124	73
	.105	173	175		.00005	52	57
	.25	95	96		.0001	0	0
	.50	0	0	Stannic chloride	.000005	141	142
Nickel chloride	.000005	170	175		.00001	140	142
	.00001	175	175		.00005	134	142
	.00005	181	175		.0001	127	100
	.0001	172	175		.0005	80	83
	.0005	110	112		.0011	40	58
	.001	50	50		.005	0	0
	.005	0	0				

[1] From data by Hotchkiss (*6*).

APPLICATION OF THE HYPOTHESIS TO THE SPROUTING OF WHEAT

The work of Jensen (*8*) furnishes an example of the application of the crossed parabolic hypothesis to green plants. Jensen used sprouted wheat seedlings in water solutions, in nutrient solutions, in sand, and in soil. He varied the concentration of the salt and measured the average length of sprout, the total transpiration, and the weight of the test specimens when green and also when dry. The grain was

sprouted before the experiments started, but since there are no data on the average dry weight or green weight at the beginning of the experiment, these figures can not be used. The statement is made, however, that the sprouts were approximately 3 mm long when the experiment was begun. The growth which takes place during the experiment is the total length recorded minus the length at the beginning. In this case, therefore, the length factor is the only factor which can be used to determine the effect of the chemical on the growth of the organism, and even this is only approximate because it must be assumed that all of the sprouts were 3 mm long. The process of preparing the data for use in this mathematical treatment involved the following steps: (1) A determination of the increase of length that took place during the experiment (total length minus 3 mm). (2) A determination of the percentage increase or decrease over the normal growth expected. (3) The empirical fitting of the data by two crossed parabolas. (4) Reading from these theoretical curves the percentage increase or decrease in the growth due to the presence of different concentrations of poisons. (5) Reconverting the percentage effect into length measurements and adding to this figure the 3 mm which was subtracted at the beginning of the calculation. This procedure gives the total length of the wheat sprout required under the theory of two reactions, one of which is stimulating, the other detrimental, and also shows that both reactions are parabolic functions of the concentration. A comparison of the results obtained by this process of calculation and empirical fitting of the data when the wheat sprouts were grown on a lead nitrate solution of various concentrations is given in Table 16. A similar comparison between the theoretical requirement and the experimental result when the wheat was grown on a nutrient solution containing various concentrations of zinc sulphate is given in Table 17.

TABLE 16.—*Comparison of calculated and experimental determination of length of wheat sprouts grown in lead nitrate solution*

Concentration	Length calculated	Length observed [1]	Concentration	Length calculated	Length observed [1]
N	*Cm*	*Cm*	*N*	*Cm*	*Cm*
0.0001	12.43	12.47	0.006	9.53	8.15
.0002	12.22	11.35	.008	9.00	8.9
.001	11.55	10.2	.01	8.60	8.92
.002	10.95	10.4	.02	7.1	7.3
.004	10.05	9.75	.04	5.3	5.3

[1] From data by Jensen (*8*).

TABLE 17.—*Comparison of calculated and experimental values of the length of wheat sprouts grown in zinc sulphate in a nutrient solution*

Concentration	Length calculated	Length observed [1]	Concentration	Length calculated	Length observed [1]
N	*Cm*	*Cm*	*N*	*Cm*	*Cm*
0.00001	13.85	13.85	0.0009	11.16	11.47
.00002	13.81	13.30	.001	10.95	10.57
.00005	13.63	14.70	.002	9.01	9.10
.0001	13.42	15.25	.004	6.70	6.90
.0003	12.69	12.77	.005	5.88	5.97
.0005	12.08	12.20	.006	4.64	5.02
.0007	11.98	11.45	.007	4.10	4.57

[1] From data by Jensen (*8*).

When, however, the plants are grown on soil the data do not follow the same laws. Jensen (*8*), however, shows that even with pure sand there is a considerable surface adsorption, so that the concentrations he records as being used in soil were certainly not the concentrations that were available to the plants. If there were a means of calculating the surface adsorption, a closer agreement might be obtained with soils. These results, while they do not prove the existence of two opposed reactions, at least show that the hypothesis is tenable and warrants further consideration.

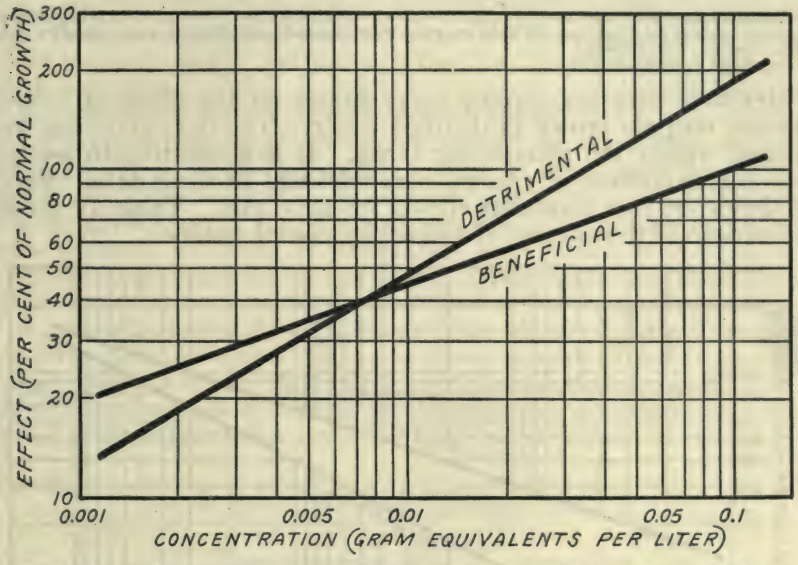


FIGURE 27.—Curves representing a beneficial and detrimental effect of manganese chloride on Canada field peas grown in soil. From data by McCool (*12*)

APPLICATION OF THE HYPOTHESIS TO GROWING PEAS

The discussion of the work of McCool (p. 33) was based on the assumption of a parabolic relationship between concentration and toxic effect. The chemicals previously discussed, however, showed the existence of a stimulating effect when used by McCool under different conditions of the experiment. In Figure 24 McCool's results on growing peas in nutrient solution with the addition of different concentrations of manganese chloride are shown as a parabolic relationship between toxic effect and concentration. Figure 27 shows two parabolas which represent McCool's results when peas are grown in soil having the same concentration of manganese chloride.[5] These results show a stimulation. The agreement of the experimental data with the curves are shown by Table 18.

[5] It is more than likely that the concentrations recorded here were not the concentrations available to the peas but are lower concentrations, due to surface adsorption of the manganese by the soil as was shown by Jensen (*8*) in his experiments with wheat.

TABLE 18.—*Comparison between the calculated and experimental values of the effect of manganese chloride on the growth of peas*

Concentration	Average length of tops		Concentration	Average length of tops	
	Calculated[1]	Observed [2]		Calculated[1]	Observed [2]
N	*Cm*	*Cm*	*N*	*Cm*	*Cm*
0	15.0	15.0	0.040	9.8	10.0
.002	16.0	16.0	.100	1.8	1.5
.020	12.6	12.5	.200	0	0

[1] Values obtained from the curves by adding the net effect to 100 per cent if the net effect is beneficial and by subtracting the net effect from 100 if the net effect is detrimental and multiplying the values by 15 (the normal growth or 100 per cent).
[2] From data by McCool (*12*).

McCool's data also supply some figures on the effect of calcium chloride on peas grown in distilled water. The data collected were entirely within the stimulating range. It is interesting to see how close the hypothesis of crossed parabolas will fit these data. Figure 28 shows the two parabolas chosen for this trial. Table 19 gives a comparison of the calculated and experimental results.

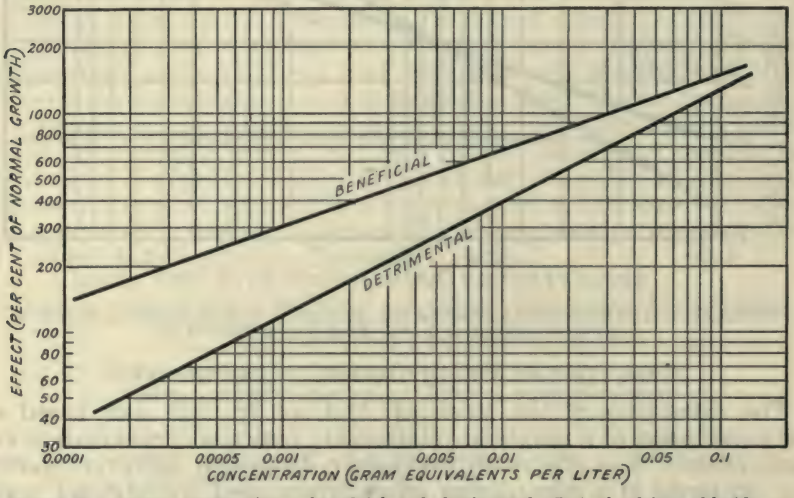


FIGURE 28.—Curves representing a beneficial and detrimental effect of calcium chloride on Canada field peas grown in distilled water. The data were collected entirely within the stimulating region. From data by McCool (*12*).

TABLE 19.—*Comparison of calculated and experimental stimulation of Canada field peas by calcium chloride*

Concentration	Weight of green tops after 30 days		Concentration	Weight of green tops after 30 days	
	Calculated[1]	Observed [2]		Calculated[1]	Observed [2]
N	*Grams*	*Grams*	*N*	*Grams*	*Grams*
0	1.85	1.85	0.01000	7.00	6.20
.10000	5.90	5.90	.00200	5.70	6.70
.04000	7.10	7.10	.00050	4.70	5.30
.02000	7.20	7.00	.00025	4.00	4.20

[1] Values obtained from the curves by adding the net effect to 100 per cent if the net effect is beneficial and by subtracting the net effect from 100 if the net effect is detrimental and multiplying the values by 1.85 (the normal growth, or 100 per cent).
[2] From data by McCool (*12*).

Only one of these values in Table 19 is as high as 1 gram difference between the experimental and theoretical results. The values therefore are certainly within the limit of measurement.

APPLICATION OF THE HYPOTHESIS TO FUNGI

At the time the experimental data shown in the early part of the bulletin were collected, no thought was given to possible stimulating effects; in fact, it was not known that timber-destroying fungi could be stimulated. It was not until the arrangement of many of the data in a form similar to the one presented that it became evident that some other influence must be at work to cause the discrepancies found in many of the data, and it was not until the idea of stimulation had been applied to Hopkins's data (p. 37) that the nature of the explanation became apparent. It was then too late to collect data on the stimulation of the test fungus. Since then Liese (*10*) has found that *Coniophora cerebella*, a wood-destroying fungus, is stimulated by dilute solutions of toxic materials. It seemed worth while, therefore, to review the experimental data on *Fomes annosus* for evidences of stimulations. Several instances of stimulation were found, some of them amounting to as much as 20 per cent. These data are much more liable to serious error than the data within the toxic range because the time during which they were growing seldom exceeded three days and never more than four and the measurements were probably not so carefully taken because they were of little interest at that time. Table 20 shows a comparison between the theoretical requirements for a pair of crossed parabolas and the observed experimental results.

TABLE 20.—*Comparison of calculated with experimental results of the effect of chrome alum on the growth of Fomes annosus*

Concentration	Radial growth		Concentration	Radial growth	
	Calculated	Observed		Calculated	Observed
Gram per liter	*Per cent of normal growth*	*Per cent of normal growth*	*Gram per liter*	*Per cent of normal growth*	*Per cent of normal growth*
0.014	128	132	0.11	3	1
.026	114	111	.14	0	0
.051	80	79			

It has now been shown that when the whole range of concentration is taken into consideration, the parabolic function must be replaced by two parabolic functions, one of which is beneficial and the other detrimental to the life of organisms, and that this relation seems to hold for bacteria, green plants, and fungi. It has also been shown that the two concepts of simple parabolic and crossed parabolic functions are compatible within the limits of the experimental error. Of the two, the concept of crossed parabolas is the more nearly complete since it covers the whole concentration range, whereas the simple parabolic relationship holds approximately only over a limited range. It is now desirable to determine whether the hypothesis of crossed parabolas can be applied to the effect of hyrdogen ions on the well-being of organisms.

APPLICATION OF THE HYPOTHESIS TO HYDROGEN ION

Investigations on the toxicity and stimulation of hydrogen ions are of interest to many fields from medicines to fertilizers because apparent small changes in the hydrogen-ion concentration may make great differences in the life of many organisms. These changes are so great that some investigators have postulated that all toxicity is founded upon the toxicity of hydrogen ions. Before the hypothesis of crossed parabolas can be applied to this type of work, it is necessary to discuss the differences between the work on hydrogen ions and work with any other ion.

(1) In all concentrations of hydrogen ions there are also present hydroxyl ions. The system of recording the concentration in pH values is such that even when the great preponderance of the ions present are not hydrogen but hydroxyl, the pH value is recorded in terms of the hydrogen ion. For the sake of clearness the number of hydrogen and hydroxyl ions in moles per liter is given in Table 21 for each whole number of pH. From Table 21 it is readily seen that a change in concentration of hydrogen ions from a pH value of 7 to a pH of 3 is not a small change but one of ten-thousand fold. A range of this magnitude is common in hydrogen-ion work. In dealing with hydrogen-ion concentrations two ions must be taken into consideration each of which may be toxic or stimulating, and at each concentration the effects of both ions must be present.

TABLE 21.—*Values of pH and their corresponding concentration of hydrogen and hydroxyl ions*

pH value	Concentration of hydrogen ions	Concentration of hydroxyl ions	pH value	Concentration of hydrogen ions	Concentration of hydroxyl ions	pH value	Concentration of hydrogen ions	Concentration of hydroxyl ions
	Moles per liter	*Moles per liter*		*Moles per liter*	*Moles per liter*		*Moles per liter*	*Moles per liter*
2	10^{-2}	10^{-12}	6	10^{-6}	10^{-8}	10	10^{-10}	10^{-4}
3	10^{-3}	10^{-11}	7	10^{-7}	10^{-7}	11	10^{-11}	10^{-3}
4	10^{-4}	10^{-10}	8	10^{-8}	10^{-6}	12	10^{-12}	10^{-2}
5	10^{-5}	10^{-9}	9	10^{-9}	10^{-5}			

(2) Though the neutral point of water as far as the electrical charge is concerned is at a pH of 7 when both ions are present in equal numbers, it is not necessarily the neutral point for fungi or bacteria any more than it is the neutral point for a large number of indicators. In fact, only the exceptional indicator correctly locates the ionic neutral point. Why certain organisms thrive best on slightly acid or slightly alkaline solutions is a very interesting speculation which need not enter into the discussion at this point, provided it is accepted that such is the case. It is only necessary to conceive that ionic neutrality is not necessarily neutrality toward any particular organism.

(3) Many fungi, bacteria, and other living organisms have the power to change the hydrogen-ion concentration of their medium, sometimes in one direction, sometimes in the other direction. Frequently this change is toward a definite pH which the organisms seem to prefer. This change is illustrated in Table 22, which is taken from the experimental data of Hopkins (*5*).

TABLE 22.—*Changes in hydrogen-ion concentration due to the growth of the fungus Gibberilla saubinetii on a liquid medium adjusted with sulphuric acid and sodium hydroxide* [1]

pH at beginning	pH after 7 days	Difference pH	pH at beginning	pH after 7 days	Difference pH	pH at beginning	pH after 7 days	Difference pH
3.85	4.4	0.55	5.5	5.5	0	7.4	5.6	1.8
4.8	3.6	1.2	5.8	6.2	.4	7.5	5.7	1.8
5.37	4.5	.87	7.5	5.2	2.3	7.6	5.9	1.7
4.8	6.0	1.2	7.5	5.2	2.3	8.25	6.9	1.3

[1] From data by Hopkins (*5*).

Curves produced by plotting growth figures (however expressed) against the pH value may be of many different patterns. The typical curve has two points of no growth—one at a high value and one at a low value of pH. As the pH increases from the low value at which no growth is obtained, the growth increases to a maximum point, then decreases to a minimum point, and then increases to a second maximum and finally decreases again to no growth at the higher pH value. Either of the maximum points may be higher than the other, and the minimum points may be either quite pronounced or scarcely noticeable.

In the previous discussion of the simple parabolic relationship and of the crossed parabolic relationship the basis of the calculation was the growth obtained in the absence of the poison. In hydrogen-ion concentration work it is not possible to obtain experimentally a growth in the absence of either hydrogen or hydroxyl ions.

A hypothetical normal growth, however, can be assumed. This assumption requires that the effect of both ions be referred to the hypothetical normal as 100 per cent normal growth. The effect of both ions will be represented by two effects—a beneficial effect and a detrimental effect—in exactly the same manner as has been done in the previous discussion, but with this difference: Each point on the curve, instead of being dependent upon a single detrimental and beneficial reaction, is in this case governed by four different reactions—a beneficial and detrimental reaction for the hydrogen ion and a beneficial and detrimental reaction for the hydroxyl ion. In other words, instead of a single pair of crossed parabolas, there are two such crossed pairs.

Inasmuch as the system of expressing hydrogen-ion concentration in terms of pH is a very convenient one and inasmuch as the pH value is the logarithm of the concentration, semilogarithmic paper may be used for plotting the curves. With semilogarithmic paper, the effect in terms of percentage of normal growth is plotted in logarithms, and the pH values are in ordinary units. Hopkins' work (*5*) on the fungus *Gibberella saubinetii* has been chosen for an example. This fungus is of great importance in agriculture, since it causes a serious disease of wheat and other small grains. Table 23 shows that this organism is capable of changing the hydrogen-ion concentration of the medium in which it grows. This change appears to be not toward the point of maximum growth but toward the minimum point. Changes of at least two pH units, which means approximately a hundredfold change in hydrogen-ion concentration, are given by Hopkins within seven days. (Table 22.) The pH value at the

beginning of the experiment is of no consequence, therefore, unless the solution were buffered. This Hopkins did in one series of tests. He records data for 4, 7, and 14 days. Even in buffered solutions the pH values are liable to change if the fungus is able to produce enough acid to use up the amount of buffer in the solution.

It might be expected, therefore, that even in buffered solutions some changes in hydrogen-ion concentration would be obtained. These changes would be more apt to be obtained in the longer period of time. Table 23 gives Hopkins' data on a buffered solution. In analyzing the data obtained after seven days a normal growth of 10

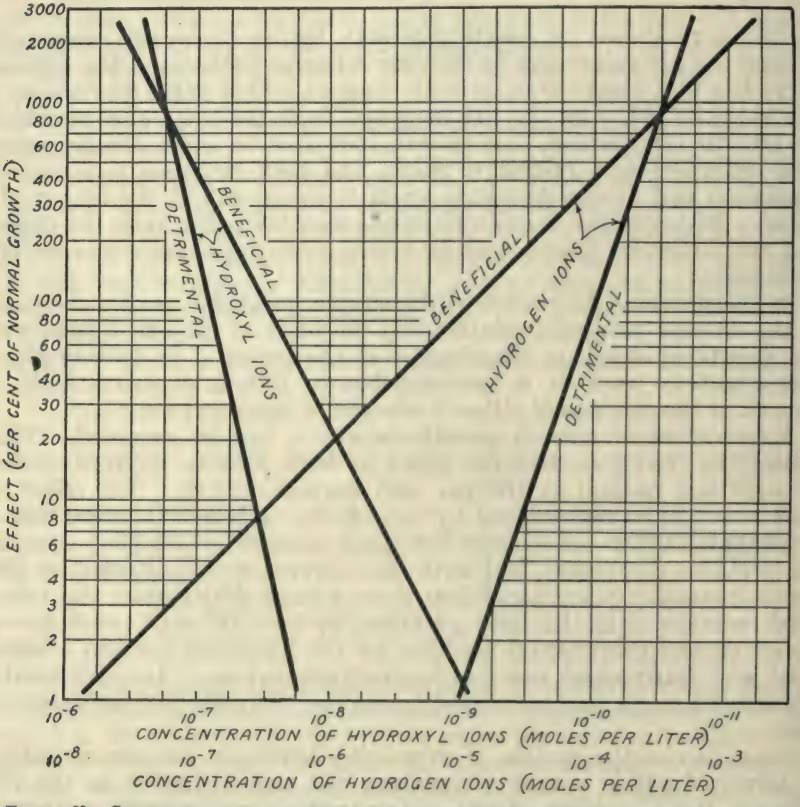


FIGURE 29.—Curves representing beneficial and detrimental effects of hydrogen and hydroxyl ions on the fungus *Gibberella saubinetii*. From data by Hopkins (*5*)

mg has been assumed, and all calculations have been based on this normal growth. Figure 29 shows the method of applying the analysis. Table 24 gives the net detrimental and net stimulating effect of each ion separately, also the total effect of both ions and the calculated total growth at the end of seven days. Figure 30 shows the calculated total growth plotted against the pH values in the usual way and a smooth curve drawn through the points thus obtained. The experimentally determined points have been added to show the accuracy with which the calculated curve fits the experimental points. Figure 31 shows the same kind of data for the 4-day period reported

by Hopkins (*5*). In this calculation the hypothetical normal growth was taken as 2. The four parabolas used in producing the two pairs of crossed parabolas were the same as were used in the previous example, with the exception of the beneficial effect of the hydroxyl ion. This lack of agreement seems to indicate that in the 7-day period some slight change in the hydrogen-ion concentration had taken place. This fact seems to explain why the same two pairs of parabolas can not be used to express the effect after 14 days. In the two periods shown the calculated results depict the experimental points well within the limits of experimental error. It seems, therefore, that the hypothesis of two pairs of crossed parabolas representing two beneficial effects and two detrimental effects—one pair for each ion—can be applied to hydrogen-ion toxicity work in exactly the same manner as it was applied to other ions.

TABLE 23.—*Hydrogen-ion concentration and growth of the fungus Gibberella saubinetii in liquid medium in which the reaction was adjusted with primary potassium phosphate, secondary potassium phosphate, phosphoric acid, and potassium hydroxide* [1]

Results after 4 days		Results after 7 days		Results after 14 days		Results after 4 days		Results after 7 days		Results after 14 days	
pH	Dry weight	pH	Dry weight	pH	Dry weight	pH	Dry weight	pH	Dry weight	pH	Dry weight
	Mg		*Mg*		*Mg*		*Mg*		*Mg*		*Mg*
2.80	0.0	2.77	0.3	2.80	2.2	6.95	3.0	6.85	28.2	7.15	71.1
2.90	.6	2.90	.8	3.15	3.6	7.10	7.0	7.10	48.8	7.45	66.1
3.05	0.0	3.10	1.8	3.25	17.2	7.10	10.6	7.15	31.7	7.55	73.2
3.40	1.8	3.47	3.8	3.85	70.6	7.10	2.8	7.20	13.6	7.70	47.8
4.25	6.0	4.60	47.4	5.00	42.2	7.15	7.8	7.20	3.2	7.75	70.8
4.75	4.8	4.60	23.4	5.40	70.4	7.15	.8	7.40	2.2	-------	-------
5.35	5.4	5.07	20.2	5.60	72.2	7.20	12.4	7.40	2.2	-------	-------
5.70	7.0	5.45	15.2	5.75	67.8	7.20	3.0	-------	-------	-------	-------
6.25	9.2	6.25	14.4	5.75	75.0						

[1] From data by Hopkins (*5*).

TABLE 24.—*Separate effect of hydrogen and hydroxyl ions and total hypothetical effect obtained with the fungus Gibberella saubinetii*

pH	Effect of hydrogen ion [1]	Effect of hydroxyl ion [1]	Sum of the effects of the hydrogen and hydroxyl ions [1]	Total effect [1]	Calculated growth [2]	pH	Effect of hydrogen ion [1]	Effect of hydroxyl ion [1]	Sum of the effects of the hydrogen and hydroxyl ions [1]	Total effect [1]	Calculated growth [2]
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Mg*		*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Mg*
3.45	−140	-------	−140	−40	-------	5.50	+40	+6	+46	+146	14.6
3.48	−60	-------	−60	+40	4.0	5.75	+27	+11	+38	+138	13.8
3.50	0	-------	0	+100	10.0	6.00	+19	+24	+43	+143	14.3
3.55	+100	-------	+100	+200	20.0	6.25	+13	+47	+60	+160	16.0
3.60	+200	-------	+200	+300	30.0	6.50	+8	+92	+100	+200	20.0
3.75	+320	-------	+320	+420	42.0	6.75	+6	+172	+178	+278	27.8
4.00	+320	-------	+320	+420	42.0	7.00	+4	+250	+254	+354	35.4
4.25	+250	-------	+250	+350	35.0	7.10	-------	+200	+200	+300	30.0
4.50	+180	-------	+180	+280	28.0	7.15	-------	+100	+100	+200	20.0
4.75	+127	-------	+127	+227	22.7	7.25	-------	0	0	100	10.0
5.00	+86	-------	+86	+186	18.6	7.28	-------	−100	−100	0	0
5.25	+59	+2	+61	+161	16.1						

[1] In terms of normal.
[2] Total effect in percentage times normal growth of 10 mgs.

DISCUSSION OF THE HYPOTHESIS

Other investigators have explained the phenomenon of a minimum growth with two maximums in different hydrogen-ion concentrations on the basis of electrical charges and membrane equilibria, basing their work on the concepts of Loeb (*11*) and his associate and treating the hydrogen-ion work as special cases. Loeb (*11*) showed that when colloidal materials such as gelatin or mastic, which are amphoteric, are suspended in aqueous solutions, and an electrical potential is applied to the solutions, the suspended particles move toward one pole if the solution is of a higher negative potential than the suspended particles; toward the other pole if the solution has a less negative potential than the suspension; and remain stationary if the solution and suspended materials are of the same charge. This movement of the suspended particles is called cataphoresis, and the rate of movement is a measure of the difference in potential of the solution and the suspended particles. If the amphoteric substance is made in the form of a membrane and held rigid in solutions of different hydrogen-ion concentration, the same type of phenomenon takes place except that the solution moves from one side to the other according to the sign of the electric charge on the membrane, and the direction of movement can be changed by changing the hydrogen-ion concentration of the solution. This movement of water is called electrical endosmose, or electrical osmose. It, too, is a measure of the potential of the membrane. When nonliving materials, such as gelatin or mastic, are used, and the rate of movement is measured, the data form curves similar in many respects to the curves produced by living organisms in different concentrations of hydrogen ions. Donnan pointed out that the similarity of the curves suggested the importance of membrane equilibrium on the life of organisms. Other investigators following this suggestion have measured both the cataphoresis and the rate of growth of the same organism. For instance, Robbins (*14*) has shown that the isoelectric point for *Rhizopus nigricans*, a mold, is approximately at pH 5. He has also shown that the growth of the mold in a stated time has a minimum at pH 5.1, which is a very good agreement between the measurements of the physical characteristics and growth characteristics of the organism. Other investigators have obtained similar results with other organisms. In Figures 30 and 31 the minimum point shifted from a pH of approximately 5 in four days to a pH of 5.75 in seven days. It would be of interest to know whether the isoelectric point

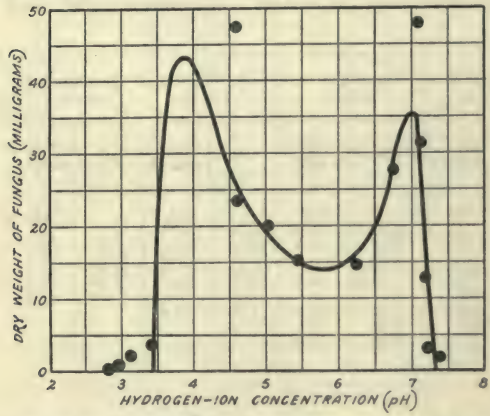


FIGURE 30.—Comparison of the hypothetical curve and the experimental results obtained with *Gibberella saubinetii* after seven days. The solid line represents the hypothetical curve, the dots the experimental data. From data by Hopkins (*5*)

also shifted and, if it did, what explanation could be given for this behavior.

Winslow, Falk, and Caulfield (*19, p. 197–198*) at the conclusion of their article on electrophoresis of bacteria, stated:

> Professor Donnan and other investigators have clearly understood the importance of applying the concept of membrane equilibria in the elucidation of physiological phenomena. Our findings add to the numerous vindications favoring this view and emphasize the importance of further study of membrane equilibria in bacterial suspensions. We have pointed out that certain potential differences between bacteria and their menstrua are apparently associated with some of the phenomena of viability. Viability and potential differences may, however, under certain conditions vary quite independently as evidenced by the fact that normal rates of migration are demonstrable after the cells have been killed by heat. Thus considerable caution must be exercised in relating the existence of these changes to the metabolism of the cell.

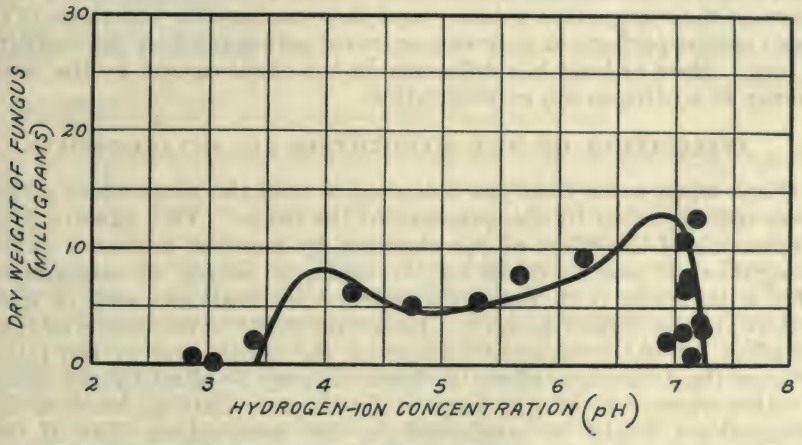


FIGURE 31.—Comparison of the hypothetical curve and the experimental results obtained with *Gibberella saubinetii* after four days. The solid line represents the hypothetical curve, the dots the experimental data. From data by Hopkins (*5*)

Loeb (*11*) showed that with suspensions of mastic, collodion, egg albumen, and gelatin the cataphoretic potential differences are the same for calcium, strontium, barium, magnesium, manganese, and cobalt. In fact he stated that, regardless of the chemical nature of the particles, the depressing influence of electrolytes on the cataphoretic potential difference is determined largely by the valency, but not by the nature, of that ion of an electrolyte which has a sign of charge opposite to that of the particle. It is well known, however, that a given concentration of calcium chloride will not have the same toxic effect upon living organisms as the same concentration of cobalt chloride although both have the same valence. Since, therefore, the toxic effect of salts, such as calcium chloride, can not be explained in terms of cataphoretic effect, why should this effect be expected to explain the toxic effect of different pH values—particularly when the same cataphoretic effect can be obtained with dead as with living organisms? It has been shown in this bulletin that the effect of hydrogen and hydroxyl ions on the well-being of the organism can be considered in exactly the same way as that of any other ions and that there is no need for a special case for hydrogen and hydroxyl ions.

Perhaps the concept of crossed parabolas also furnishes the clue (p. 42) to the reason why certain organisms have a minimum-growth point at one pH and others show a minimum growth point at some other pH. A change in the slope of any of the four parabolas will change the minimum point.

The similarity of the cataphoretic effect and the physiological effect in hydrogen-ion work can be explained on the following basis: Both effects are dependent upon the concentration of both the hydrogen or hydroxyl ions. Both would be a measure of the same thing and, therefore, changes in the hydrogen-ion concentration should, in general, give the same type of curve. There is this difference, however, that the physiological effect first shows an acceleration of growth followed by a rapid depression until no physiological effect can be produced at certain concentrations. Amphoteric membrances first increase their migration velocity and then decrease it, but there is no point except perhaps in very concentrated solution where the velocity is zero. Here at least is a difference in the effect caused by the same change in hydrogen-ion concentration.

APPLICATION OF THE HYPOTHESIS TO ANTAGONISM

Often when more than one chemical is used the toxic effect of the more toxic is offset by the presence of the other. This offsetting, or minimizing of the effect of one chemical by another, is known as the antagonism of one chemical for the other, or simply as antagonism. This antagonism is of particular interest in medicine and in agriculture; in the former because a poisonous effect of one material may be offset by the antagonistic effect of the other, and in the latter because the deleterious effect of chemicals may be offset by the action of other chemicals in the form of fertilizers. Part at least of the antagonisms might be explained on the assumption that, if one chemical were used at a concentration whose net effect was beneficial and the other at a concentration whose net effect was detrimental, the two effects would tend to neutralize each other. If then the effect of the two compounds were known independently, it might be possible to calculate the effect of both combined on the assumption that the combined effect would be the algebraic sum of their individual effects at the same concentration. McCool's work referred to on page 33 furnishes a number of results which might serve as a test for this idea.

Nowhere in McCool's results (*12*) is it possible to gather data showing the total effect of manganese chloride. Fortunately, however, McCool presents growth data for peas grown in different concentrations of both manganese chloride and calcium chloride, and also the growth data for the control. From these data the effect of any particular concentration of manganese chloride and calcium chloride can be calculated directly. For example, McCool gives the weight of the green tops of 10 peas in distilled water as 1.85 g, and in N/10 calcium chloride as 5.90 g. Taking the 1.85 g as representing the normal growth, the N/10 calcium chloride stimulated the growth 4.05 g, or 219 per cent. The growth obtained with N/4000 manganese chloride was 1.80 g; that is, a retarding effect of 0.05 g, or −3 per cent. The sum of the two effects if peas were grown on N/10 calcium chloride plus N/4000 manganese chloride should be 219 −3, or 216

per cent stimulation, or 4.01 g in excess of the 1.85 g normal growth. The expected growth is therefore 5.85 g. McCool found 5.76 g experimentally. Other data calculated in the same manner are given in Table 25.

TABLE 25.—*Comparison of the calculated and experimental results of the weight of the green tops of Canada field peas grown 30 days in mixtures of calcium and manganese chloride in distilled water*

Mixture	Calculated	Observed [1]	Difference
	Grams	*Grams*	*Grams*
N(0.1) $CaCl_2$+N(0.001) $MnCl_2$	3.94	5.12	−1.18
[2]N(0.1) $CaCl_2$+N(0.0005) $MnCl_2$	5.15	5.14	+.01
N(0.1) $CaCl_2$+N(0.00025) $MnCl_2$	5.85	5.76	+.09
N(0.04) $CaCl_2$+N(0.001) $MnCl_2$	5.25	4.52	+.73
N(0.01) $CaCl_2$+N(0.001) $MnCl_2$	5.10	5.56	−.46
N(0.002) $CaCl_2$+N(0.001) $MnCl_2$	4.35	3.75	+.60
N(0.0005) $CaCl_2$+N(0.001) $MnCl_2$	3.40	3.45	−.05
N(0.00025) $CaCl_2$+N(0.001) $MnCl_2$	2.40	2.01	+.40

[1] From data by McCool (*12*).
[2] Effect of this concentration of $MnCl_2$ estimated from curve of $MnCl_2$ alone.

The agreement between the calculated and experimental results given in Table 23 is fair when it is considered that each calculation may involve two experimental errors and that the experimental result may also contain some errors. Similar agreements with other pairs of chemicals can be shown from McCool's data, but these are sufficient to indicate that at times the antagonistic effect can be calculated from a simple consideration of effect produced by each chemical taken alone. McCool (*12*) also presents data on the effects produced by growing peas in nutrient solution containing different combinations of calcium chloride and manganese chloride. This should also be capable of calculation if the effect of the nutrient solution can be estimated. The nutrient solution was made up as follows: Calcium nitrate, 4 g; potassium monophosphate, 1 g; potassium nitrate, 1 g; magnesium sulphate, 1 g; potassium chloride, 0.5 g; ferric chloride, 0.1 g; distilled water, 3 liters.

Peas grown in distilled water produced green tops in 30 days that weighed 1.85 g. Peas grown on the foregoing nutrient solution produced 10.40 g of tops in the same time. The difference between the two weights represents a simulation of the solution of 8.55 g, or 462 per cent.

Since this is an attempt to calculate the antagonistic effect of calcium and manganese in nutrient solution and since the nutrient solution contained calcium, it is necessary further to factor the effect of the nutrient solutions. The concentration of calcium in the nutrient solution was N/0.016. In Figure 28 the stimulation of this concentration; that is, the difference between the beneficial and detrimental effects, is calculated as 300 per cent. The stimulation of the nutrient solution is about 460 per cent of the growth in distilled water, 300 per cent of this is due to calcium and 160 per cent is due to elements other than calcium or manganese. The figure 0.016 was added to the concentration of the calcium chloride used in nutrient solution to determine the total concentration of calcium.

The solutions of manganese chloride used in this experiment were much more concentrated than those in some of the previous experi-

ments of McCool, so that for the most part the effect of manganese chloride alone is unknown. This effect can, however, be calculated if it be assumed that the effect of manganese chloride in nutrient solution is made up of (1) a stimulating action of the sclution and (2) an effect of the manganese. (Table 26.)

TABLE 26.—*Calculation of the effect of manganese chloride in a nutrient solution on the growth of peas*

Item	Grams	Percentage of normal growth
Normal growth of peas in distilled water	1.85	
Growth in nutrient solution	10.40	[1] 462
Growth in nutrient solution containing N/100 $MnCl_2$	2.25	[1] 22
Detrimental effect of N/100 $MnCl_2$		440

[1] Stimulating.

Values for N/50, N/200, N/500 manganese chloride have been worked out in a similar manner to that shown in Table 26. These taken with data obtained from McCool's experiments in distilled water were plotted on logarithmic paper to get the most probable effect in distilled water of manganese chloride at all ranges of toxic concentrations.

The total effect of calcium and manganese in nutrient solution is therefore made up of four factors: (1) Normal growth in distilled water; (2) effect of the chemicals other than calcium in the nutrient solution; (3) the effect of the calcium chloride referred to its effect in distilled water; (4) effect of the manganese chloride referred to its effect in distilled water. Each of these effects has been estimated separately. It is only necessary now to combine them. This has been done in Table 27.

TABLE 27.—*Comparison of calculated and experimental results of the weight of green tops of Canada field peas grown 30 days in different concentrations of calcium chloride and manganese in nutrient solution*

Concentration			Effect in terms of normal growth				Growth	
Calcium chloride		Manganese chloride, recorded	Calcium chloride	Manganese chloride	Nutrient solution except calcium	Total effect	Calculated	Observed [1]
Recorded	Actual							
N	*N*	*N*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Grams*	*Grams*
0.100	0.116	0.020	+200	−520	+160	−160	0	0.50
.100	.116	.010	+200	−420	+160	−60	.74	5.05
.100	.116	.002	+200	−180	+160	+180	5.18	7.35
.020	.036	.020	+300	−520	+160	−60	.74	.45
.020	.036	.010	+300	−420	+160	+40	2.59	2.55
.010	.026	.020	+300	−520	+160	−60	.74	.35
.010	.026	.010	+300	−420	+160	+40	2.59	2.55
.010	.026	.002	+300	−180	+160	+280	7.05	7.19
.002	.018	.020	+300	−520	+160	−60	.74	.37
.002	.018	.010	+300	−420	+160	+40	2.59	2.10
.002	.018	.005	+300	−300	+160	+160	4.81	3.15
.001	.017	.010	+290	−420	+160	+30	2.40	1.60
.001	.017	.005	+290	−300	+160	+150	4.62	2.10

[1] From data by McCool (*12*).

The agreement of the calculated with the experimental results is by no means perfect. It is believed, however, that all but one of them are within the ranges of experimental error and the error of calculation. The basis for the calculation was the weight of the green tops grown in distilled water. This was used to calculate the percentage effect of the nutrient solution. A variation in this basis would make an enormous variation in the calculated results. A variation from 1.85 g to 2.10 g in the weight of the green tops in distilled water would have made all the experimental results higher than the caluclated results and would have given negative growth for three of the calculated figures. McCool (*12*) does not give many determinations of the weight of the green tops grown for 30 days but he does give a number of such determinations after 24 days' growth. These are shown below. With so large a variation in the basis of calculation all but one of the 13 calculations in Table 27 would be considered as check results.

Experiment No.	Weight of green tops	Experiment No.	Weight of green tops
	Grams		*Grams*
1	1.72	5	1.85
2	1.70	6	1.70
3	1.82	7	1.65
4	2.20	8	1.75

It is therefore evident that some of the data on the antagonistic action of one salt for another can be explained entirely by a consideration of a stimulating and retarding action as presented here. The complete explanation is yet imperfect, just as the explanation presented by representing the toxic action by a simple parabolic function of the concentration was shown to be imperfect. The method of calculation presented here does not and can not explain the stimulating effect obtained by combining two compounds each in concentrations which alone would give a toxic action. In order to do this it seems necessary that the concentrations used in some way be reduced until at least one of the chemicals produces a stimulating action. Little is known about the concentration of chemicals within living membranes. Genearlly it has been supposed that these concentrations are the same as in the solutions upon which the organisms grew, or at least that the equilibrium between the concentration within the membranes is in some direct ratio to the concentration in the solutions. This equilibrium between the concentration on either side of a membrane might be upset very easily by the presence of another constituent. The theory of membrane equilibrium brought out by Donnan probably provides the basis for future extension of the work on antagonism. If the living membrane is amphoteric and contains ionized but nondiffusible compounds, or is capable of forming such compounds, then very different concentrations may exist in equilibrium conditions on either side of such a membrane. Calculations on the effect of such amphoteric membranes require a knowledge of the base combined with the membrane or the proportion of each base combined with the membrane if more than one could be combined at the same time. This information is not available. Analysis of the ash of roots of plants grown in mixtures of antagonistic compounds

should be of interest in this connection since it might give some idea of the ratio of the materials within the membranes in comparison with the ratio of the same materials outside the membranes.

SUMMARY AND CONCLUSIONS

The normal radial growth of the fungus *Fomes annosus* is directly proportional to the time of growth, provided other conditions are the same.

The radial growth of the fungus *Fomes annosus* is directly proportional to time even when poisonous materials are added to its food supply, provided other conditions are the same and the concentration of the poison is not lethal.

The change in the rate of growth of the fungus *Fomes annosus* due to the presence of a poison appears, within limits, to be proportional to a parabolic function of the concentration of the poison and can be expressed by the equation $R=DC^n$, in which R is the percentage retardation, C the concentration, and D and n are constants.

The constant D in the equation $R=DC^n$ may vary with each individual material, but the exponent n appears to be dependent upon the constitution of the poison. The exponent n has one value if the poison is an inorganic salt with a poisonous basic radical, another value if the poison is an ortho substituted benzene derivative, and still another value if it is a para or meta substituted benzene derivative.

The idea that toxic action can be expressed as a parabolic function of the concentration appears to be applicable, within limits, to other organisms, such as aphids, bacteria, and green plants.

Stimulation and toxic action can be regarded as different phases of a pair of opposed reactions.

The whole range of physiological effect of a poison can be represented by the difference between crossed curves both of which are parabolic functions of the concentration.

The physiological effect caused by changing the hydrogen-ion concentration can be represented by the sum of the effects produced by both hydrogen and hydroxyl ions each of which can be represented by the difference between two curves which are parabolic functions of their respective concentrations.

A partial explanation of antagonism, based on the hypothesis developed from the previous work, is offered.

LITERATURE CITED

(1) CHICK, H.
1908. AN INVESTIGATION OF THE LAWS OF DISINFECTION. Jour. Hyg. [London] 8:92–158, illus.

(2) COHEN, B.
1922. DISINFECTION STUDIES: THE EFFECTS OF TEMPERATURE AND HYDROGEN ION CONCENTRATION UPON THE VIABILITY OF BACT. COLI AND BACT. TYPHOSUM IN WATER. Jour. Bact. 7:183–230, illus.

(3) FALCK, R.
1907. WACHSTUMGESETZE, WACHSTUMFAKTOREN UND TEMPERATURWERTE DER HOLZZERSTÖRENDEN MYCELIEN. *In* Möller, A. Hausschwammforschungen in amtlichen Auftrage. 1:[53]–154, illus.

(4) GLASER, W. R.
1927. ZUR THEORIE DER GIFT WIRKUNGEN (BEZIEHUNG ZWISCHEN KONZENTRATION UND EINWIRKUNGSZEIT.) Ztschr. Gesam. Espt. Med. 56:410–432, illus.

(5) HOPKINS, E. F.
1922. HYDROGEN-ION CONCENTRATION IN ITS RELATION TO WHEAT SCAB. Amer. Jour. Bot. 9:159–179, illus.
(6) HOTCHKISS, M.
1923. STUDIES ON SALT ACTION. VI. THE STIMULATING AND INHIBITIVE EFFECT OF CERTAIN CATIONS UPON BACTERIAL GROWTH. Jour. Bact. 8:141–162, illus.
(7) HUMPHREY, C. J., and FLEMING, R. M.
1915. THE TOXICITY TO FUNGI OR VARIOUS OILS AND SALTS, PARTICULARLY THOSE USED IN WOOD PRESERVATION. U. S. Dept. Agr. Bul. 227, 38 p., illus.
(8) JENSEN, G. H.
1907. TOXIC LIMITS AND STIMULATION EFFECTS OF SOME SALTS AND POISONS ON WHEAT. Bot. Gaz. 43:11–44, illus.
(9) KRÖNIG, B., and PAUL, T.
1897. DIE CHEMISCHEN GRUNDLAGEN DER LEHRE VON DER GIFT WIRKUNG UND DESINFECTION. Ztschr. Hyg. u. Infectionskrank. 25:1–112.
(10) LIESE, J.
1931. BEOBACHTUNGEN ÜBER DIE BIOLOGIE HOLZZERSTÖRENDER PILZE. Ztschr. Angew. Bot. 13:138–150, illus.
(11) LOEB, J.
1924. HYDROPHILIC AND HYDROPHOBIC COLLOIDS AND THE INFLUENCE OF ELECTROLYTES ON MEMBRANE POTENTIALS AND CATAPHORETIC POTENTIALS. Jour. Gen. Physiol. 6:307–328, illus.
(12) MCCOOL, M. M.
1913. THE ACTION OF CERTAIN NUTRIENT AND NON-NUTRIENT BASES ON PLANT GROWTH—I. THE ANTITOXIC ACTION OF CERTAIN NUTRIENT AND NON-NUTRIENT BASES WITH RESPECT TO PLANTS. N. Y. (Cornell) Expt. Sta. Mem. 2, p. 121–216, illus.
(13) RICHARDS, C. A.
1923. METHODS OF TESTING THE RELATIVE TOXICITY OF WOOD PRESERVATIVES. Amer. Wood Preservers' Assoc. Proc. 19:127–135.
(14) ROBBINS, W. J.
1924. ISOELECTRIC POINTS FOR THE MYCELIUM OF FUNGI. Jour. Gen. Physiol. 6:259–271, illus.
(15) TATTERSFIELD, F., GIMINGHAM, C. T., and MORRIS. H. M.
1925. STUDIES ON CONTACT INSECTICIDES. PART I. INTRODUCTION AND METHODS. PART II. A QUANTITATIVE EXAMINATION OF THE TOXICITY OF TEPHROSIA VOGELII HOOK TO APHIS RUMICIS L. (THE BEAN APHIS.) Ann. Appl. Biol. 12:61–76, illus.
(16) ——— GIMINGHAM, C. T., and MORRIS, H. M.
1925. STUDIES ON CONTACT INSECTICIDES. PART III. A QUANTITATIVE EXAMINATION OF THE INSECTICIDAL ACTION OF THE CHLOR-, NITRO-, AND HYDROXYL DERIVATIVES OF BENZENE AND NAPHTHALENE. Ann. Appl. Biol. 12:218–262, illus.
(17) ——— GIMINGHAM, C. T., and MORRIS, H. M.
1926. STUDIES ON CONTACT INSECTICIDES. PART IV. A QUANTITATIVE EXAMINATION OF THE TOXICITY OF CERTAIN PLANTS AND PLANT PRODUCTS TO APHIS RUMICIS, L. (THE BEAN APHIS.) Ann. Appl. Biol. 13:424–445, illus.
(18) WINSLOW, C. E. A., and FALK, I. S.
1923. STUDIES ON SALT ACTION. VIII. THE INFLUENCE OF CALCIUM AND SODIUM SALTS AT VARIOUS HYDROGEN ION CONCENTRATIONS UPON THE VIABILITY OF BACTERIUM COLI. Jour. Bact. 8:215–236.
(19) ——— FALK, I. S., and CAULFIELD, M. F.
1923. ELECTROPHORESIS OF BACTERIA AS INFLUENCED BY THE HYDROGEN-ION CONCENTRATION AND THE PRESENCE OF SODIUM AND CALCIUM SALTS. Jour. Gen. Physiol. 6:177–200, illus.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Forest Service	R. Y. STUART, *Chief.*
Branch of Research	EARLE H. CLAPP, *Assistant Forester, in Charge.*
Forest Products Laboratory	CARLILE P. WINSLOW, *Director.*
Section of Derived Products	E. C. SHERRARD, *Principal Chemist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

TECHNICAL BULLETIN No. 345 FEBRUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

BIOLOGY AND MORPHOLOGY OF THE SPINDLE WORM, OR ELDER BORER[1]

By J. C. SILVER,[2] formerly *Assistant Entomologist, Division of Cereal and Forage Insects, Bureau of Entomology*[3]

CONTENTS

	Page		Page
Introduction	1	Life history and habits—Continued.	
Character and extent of injury to corn	2	Pupal cells	14
Historical	2	Prepupa	14
Distribution	3	Pupa	14
Food plants	4	Longevity of adults	14
Character and extent of injury to elder	4	Seasonal development	14
Description of *Achatodes zeae*	6	Artificial dissemination	15
The egg	6	Natural dissemination	15
The larva	6	Natural control	15
The pupa	8	Parasites	15
The adult	8	Birds and rodents	18
Experimental methods	10	Artificial control	18
Life history and habits	10	Summary	18
The moth	10	Literature cited	18
The larva	11		

INTRODUCTION

The spindle worm or elder borer (*Achatodes zeae* Harr.) is primarily a pest of the elder shrub (Sambucus [Tourn.] L.) but has been recorded (*7, p. 318; 4, p. 791*)[4] as injurious to corn plants. The first report of this insect as injuring corn was made by T. W. Harris of Massachusetts in 1841 (*7, p. 318*). He referred to the species "known to our farmers as the spindle worm" and said that "the insect receives its common name from its destroying the spindle [tassel] of the Indian corn" just before it becomes visible above the enveloping tuft of leaves at the top of the plant. The writer has searched for *A. zeae* in various plants growing in close proximity to infested elder clumps but has failed to find it in any plant other than elder.

The investigations reported in this bulletin were conducted from the European corn borer laboratory at Toledo, Ohio, most of the field observations being made in the district immediately surround-

[1] *Achatodes zeae* (Harr.); order Lepidoptera, family Noctuidae.

[2] Mr. Silver was transferred to the Bureau of Plant Quarantine on Apr. 16, 1931.

[3] The writer is greatly indebted to D. J. Caffrey, of the Bureau of Entomology, for his interest, enthusiasm, helpful suggestions, and instructive criticism, and to Carl Heinrich, W. R. Walton, and Philip Luginbill, of the same bureau, for their corrections and suggestions. Acknowledgment of assistance from others is made at various places throughout the bulletin.

[4] Italic numbers in parentheses refer to Literature Cited, p. 18.

150932°—33——1

ing that point. The study of this insect was made because of reports that it attacked corn and because the larva is sometimes mistaken for the European corn borer (*Pyrausta nubilalis* Hbn.).

CHARACTER AND EXTENT OF INJURY TO CORN

The following quotation is taken from a description by Harris (*7, p. 318–319*) of the injury caused by this insect to corn:

> This insect receives its common name from its destroying the spindle of Indian corn; but its ravages generally begin while the corn-stalk is young, and before the spindle rises much above the tuft of leaves in which it is embosomed. The mischief is discovered by the withering of the leaves, and, when these are taken hold of, they may often be drawn out with the included spindle. On examining the corn, a small hole may be seen in the side of the leafy stalk, near the ground, penetrating into the soft centre of the stalk, which, when cut open, will be found to be perforated, both upwards and downwards, by a slender worm-like caterpillar, whose excrementitious castings surround the orifice of the hole.

A similar description of the character of injury by *A. zeae* to corn was made by W. O. Ellis (*4, p. 791*).

Spindle-worm attack on young corn causes the plant to wither and fall over, thus rendering its presence more noticeable in corn than in elder. In records of attacks on corn, it is usually mentioned that such corn was grown near elder bushes and that the infestation in the corn plants was apparently occasioned by migration from the elder. However, in the instance cited by Harris the proximity of the injured corn to infested elder is not indicated. Ellis (*4, p. 791*) mentions that elder was growing closely adjacent to the corn found infested by *A. zeae*.

According to Harris (*7, p. 318–319*), corn plants that are attacked usually wither and die. However, as this insect rarely attacks corn, and even then attacks only a few plants, the species is not considered to be of great economic importance to corn.

HISTORICAL

Harris's original article on the spindle worm (*7, p. 318–320*) included a brief description of the insect and its habits. Since this description has caused some discussion it seems desirable to quote it from the article. It is as follows:

> These insects are fatal to the plants attacked, the greater part of which however, are without value to the farmer. Indian corn must be excepted; for it often suffers severely from the depredations of one of these Nonagrians, known to our farmers by the name of spindle-worm. The Rev. L. W. Leonard has favored me with a specimen of this insect, its chrysalis, and its moth, together with some remarks upon its habits; and the latter have also been described to me by an intelligent friend conversant with agriculture. * * * This caterpillar grows to the length of an inch, or more, and to the thickness of a goose-quill. It is smooth, and apparently naked, yellowish, with the head, the top of the first and of the last rings black, and with a band across each of the other rings, consisting of small, smooth, slightly elevated, shining black dots, arranged in a double row. With a magnifying glass a few short hairs can be seen on its body, arising singly from the black dots. This mischievous caterpillar is not confined to Indian corn, it attacks also the stems of the Dahlia, as I am informed, both by Mr. Leonard, and by the Rev. J. L. Russell, both of whom have observed its ravages in the stems of this favorite flower. The chrysalis, which is lodged in the burrow formed by the spindle-worm, is slender, but not quite so long in proportion to its thickness as those of most Nonagrians. It is shining

mahogany-brown, with the anterior edges of four of the rings of the back roughened with little points, and four short spines or hooks, turned upwards, on the hinder extremity of the body. The moth produced from this insect differs from the other Nonagrians somewhat in form, its fore-wings being shorter, and more rounded at the tip. It may be called *Gortyna*[5] *Zeæ*, the corn Gortyna; Zea being the botanical name of Indian corn. The fore-wings are rust-red; they are mottled with gray, almost in bands, uniting the ordinary spots, which are also gray and indistinct; there is an irregular tawny spot near the tip, and on the veins there are a few black dots. The hind-wings are yellowish gray, with a central dusky spot, behind which are two faint, dusky bands. The head and thorax are rust-red, with an elevated tawny tuft on each. The abdomen is pale brown, with a row of tawny tufts on the back. The wings expand nearly one inch and a half.

In order to check the ravages of these insects they must be destroyed while in the caterpillar state. As soon as our corn-fields begin to show, by the withering of the leaves, the usual signs that the enemy is at work in the stalks, the spindle-worms should be sought for and killed; for, if allowed to remain undisturbed until they turn to moths, they will make their escape, and we shall not be able to prevent them from laying their eggs for another brood of these

CORRECTION

Technical Bulletin No. 345, United States Department of Agriculture, Biology and Morphology of the Spindle Worm, or Elder Borer.

Page 14. In the fifth line of the seventh paragraph, "July 4" should be "June 4."

ing *A. zeae* with
es an account of
corn by Harris.
cing *A. zeae*, but
life-history data
d *A. zeae* attack-

elder along the
thern Michigan.
lantly in Massa-
3, p. 174) gives
orbes (*5, p. 85*)
p. 218) recorded
that it has been
his insect rather
Washington has

specimens that were collected in the following States: Florida, Louisiana, Tennessee, Alabama, North Carolina, Maryland, Maine, Missouri, Illinois, New York, Pennsylvania, Connecticut, Iowa, and in the District of Columbia. C. E. Smith,[6] of the United States Bureau of Entomology, reports that he made several collections in the vicinity of Baton Rouge, La. Without doubt, *A. zeae* has a greater range of distribution than that already listed, as elder is found in nearly all the States of the Union. Mathews (*8, p. 400*) says that the American elder (*Sambucus canadensis* L.) is common in rich moist lowlands, mostly in thickets, and is distributed from Nova Scotia to Florida, and westward to Manitoba, eastern Kansas, Arizona, and Texas and that it ascends to an altitude of 3,500 feet in the Allegheny Mountains. *S. racemosa* L., a similar shrub, is distributed from Newfoundland to Nova Scotia, west to British Columbia, Michigan, Iowa, Colorado, and south to Georgia.

[5] Gortyna, in ancient geography, was the name of a city in Crete, so called from its founder.

[6] Letter to J. C. Silver, dated March 14, 1930.

ing that point. The study of this insect was made because of reports that it attacked corn and because the larva is sometimes mistaken for the European corn borer (*Pyrausta nubilalis* Hbn.).

CHARACTER AND EXTENT OF INJURY TO CORN

The following quotation is taken from a description by Harris (*7, p. 318–319*) of the injury caused by this insect to corn:

This insect receives its common name from its destroying the spindle of Indian corn; but its ravages generally begin while the corn-stalk is young, and before the spindle rises much above the tuft of leaves in which it is embosomed. The mischief is discovered by the withering of the leaves, and, when these are taken hold of, they may often be drawn out with the included spindle. On examining the corn, a small hole may be seen in the side of the leafy stalk, near the ground, penetrating into the soft centre of the stalk, which, when cut open, will be found to be perforated, both upwards and downwards, by a slender wormlike caterpillar, whose excrementitious castings surround the orific

A similar descript
was made by W. O.

Spindle-worm att
and fall over, thus
than in elder. In
tioned that such co
infestation in the co
tion from the elder.
proximity of the i
Ellis (*4, p. 791*) m
to the corn found in

According to Ha
tacked usually with
tacks corn, and eve
not considered to b

Harris's original
cluded a brief description of the insect and its habits. Since this description has caused some discussion it seems desirable to quote it from the article. It is as follows:

These insects are fatal to the plants attacked, the greater part of which however, are without value to the farmer. Indian corn must be excepted; for it often suffers severely from the depredations of one of these Nonagrians, known to our farmers by the name of spindle-worm. The Rev. L. W. Leonard has favored me with a specimen of this insect, its chrysalis, and its moth, together with some remarks upon its habits; and the latter have also been described to me by an intelligent friend conversant with agriculture. * * * This caterpillar grows to the length of an inch, or more, and to the thickness of a goose-quill. It is smooth, and apparently naked, yellowish, with the head, the top of the first and of the last rings black, and with a band across each of the other rings, consisting of small, smooth, slightly elevated, shining black dots, arranged in a double row. With a magnifying glass a few short hairs can be seen on its body, arising singly from the black dots. This mischievous caterpillar is not confined to Indian corn, it attacks also the stems of the Dahlia, as I am informed, both by Mr. Leonard, and by the Rev. J. L. Russell, both of whom have observed its ravages in the stems of this favorite flower. The chrysalis, which is lodged in the burrow formed by the spindle-worm, is slender, but not quite so long in proportion to its thickness as those of most Nonagrians. It is shining

mahogany-brown, with the anterior edges of four of the rings of the back roughened with little points, and four short spines or hooks, turned upwards, on the hinder extremity of the body. The moth produced from this insect differs from the other Nonagrians somewhat in form, its fore-wings being shorter, and more rounded at the tip. It may be called *Gortyna*[5] *Zeæ*, the corn Gortyna; Zea being the botanical name of Indian corn. The fore-wings are rust-red; they are mottled with gray, almost in bands, uniting the ordinary spots, which are also gray and indistinct; there is an irregular tawny spot near the tip, and on the veins there are a few black dots. The hind-wings are yellowish gray, with a central dusky spot, behind which are two faint, dusky bands. The head and thorax are rust-red, with an elevated tawny tuft on each. The abdomen is pale brown, with a row of tawny tufts on the back. The wings expand nearly one inch and a half.

In order to check the ravages of these insects they must be destroyed while in the caterpillar state. As soon as our corn-fields begin to show, by the withering of the leaves, the usual signs that the enemy is at work in the stalks, the spindle-worms should be sought for and killed; for, if allowed to remain undisturbed until they turn to moths, they will make their escape, and we shall not be able to prevent them from laying their eggs for another brood of these pestilent insects.

Ellis (*4, p. 791*) wrote an article in 1925 comparing *A. zeae* with the European corn borer. Forbes (*5, p. 85*) includes an account of its activities because it had been reported as a pest of corn by Harris. Balduf (*1, p. 218*) has discussed the parasites attacking *A. zeae*, but Breakey (*2, p. 175*) gives a record of parasites and life-history data and mentions in his article that he was unable to find *A. zeae* attacking the red-berried elder (*Sambucus racemosa* L.).

DISTRIBUTION

The spindle worm was found rather abundantly in elder along the roadsides in the vicinity of Toledo, Ohio, and in southern Michigan. Ellis (*4, p. 791*) reports it as occurring rather abundantly in Massachusetts and attacking corn in that State. Dyar (*3, p. 174*) gives its distribution as in the North Atlantic States. Forbes (*5, p. 85*) reports it as being common in Illinois. Balduf (*1, p. 218*) recorded it as being present in Illinois and Ohio and stated that it has been found in Michigan. Breakey (*2, p. 175*) found this insect rather abundant in Wisconsin. The National Museum at Washington has specimens that were collected in the following States: Florida, Louisiana, Tennessee, Alabama, North Carolina, Maryland, Maine, Missouri, Illinois, New York, Pennsylvania, Connecticut, Iowa, and in the District of Columbia. C. E. Smith,[6] of the United States Bureau of Entomology, reports that he made several collections in the vicinity of Baton Rouge, La. Without doubt, *A. zeae* has a greater range of distribution than that already listed, as elder is found in nearly all the States of the Union. Mathews (*8, p. 400*) says that the American elder (*Sambucus canadensis* L.) is common in rich moist lowlands, mostly in thickets, and is distributed from Nova Scotia to Florida, and westward to Manitoba, eastern Kansas, Arizona, and Texas and that it ascends to an altitude of 3,500 feet in the Allegheny Mountains. *S. racemosa* L., a similar shrub, is distributed from Newfoundland to Nova Scotia, west to British Columbia, Michigan, Iowa, Colorado, and south to Georgia.

---

[5] Gortyna, in ancient geography, was the name of a city in Crete, so called from its founder.

[6] Letter to J. C. Silver, dated March 14, 1930.

The writer has records of *A. zeae* attacking *S. racemosa* in Morgan Township, Ashtabula County, and Vermilion Township, Erie County, Ohio, and in Oxford Township, Oakland County, Mich.

Severe damage by this pest to the golden American elder (*S. canadensis aurea*) and the cutleaf American elder (*S. canadensis acutiloba*) was apparent at Toledo, Ohio, where these two varieties were planted for ornamental purposes on the grounds of the Toledo Zoological Park. R. T. Everly, of the United States Bureau of Entomology, found the spindle worm attacking *S. canadensis aurea* in Conneaut Township, Erie County, Ohio.

FOOD PLANTS

Elder (*S. canadensis*, *S. racemosa*, *S. canadensis aurea*, and *S. canadensis acutiloba*) is its most common host. Corn and dahlia[7] have been recorded as rare hosts.

In an experiment conducted at Bono, Ohio, the writer confined several larvae of *Achatodes zeae* in a small cage containing elder and young corn plants, to determine whether the larvae would migrate from the elder to the corn. In this test the elder was severely damaged, all the young shoots becoming badly withered, but the larvae failed to migrate to the corn planted among the elder plants. In another test the *A. zeae* larvae failed to migrate to corn that was planted out of doors near a large group of infested elder bushes.

CHARACTER AND EXTENT OF INJURY TO ELDER

Characteristic injury by this insect to elder is not so noticeable as is that of many other insects, as the work is confined principally to the pithy portion inside the annual shoots; but the heap or mound of frass at the base of the injured stalk and the castings at the entrance hole (fig. 1) can be detected by the trained observer. With the continued feeding and boring of the larva this frass increases in bulk and accumulates around the base of the infested stalk.

The activity of the larva in the dead, dry branches before pupation results in the accumulation of a thin layer of fine sawdustlike material near the point of attack. Its early feeding on the new foliage in the spring is not superficially noticeable, as this feeding is slight and occurs within the unfolding leaf curls. The larva feeds for a few days within the curl before it bores into the new shoots. Usually it remains within its originally selected shoot until the food supply is exhausted, then it migrates to quarters where more succulent food is afforded. The entrance to the lateral stems, or shoots, is usually made on the upper side and near the base of the shoot.

Regarding the actual damage to elder, the writer has not observed any loss that could be considered of economic importance, with the exception of the damage caused to the ornamental varieties of *Sambucus canadensis* L., listed horticulturally as *S. aurea* and *S. acutiloba*. Although the young ground shoots of elder suffered great damage, only a few of them were injured to the extent of causing their death. However, the seriously injured shoots failed to pro-

[7] There has been doubt as to whether the larvae found in dahlia were *A. zeae* but, as there is no way of disproving this record, Harris's statement should be accepted.

duce new shoots the following spring. Had these ground shoots been under commercial cultivation, the injury caused by this insect could have been considered of economic importance. In 1929 and

FIGURE 1.—Entrance holes of the spindle worm (*Achatodes zeae*) in ground shoots of elder. Note frass at base of holes on portions of stalks

1930 the ground shoots and several of the lateral shoots of the ornamental varieties located at Walbridge Park, Toledo, Ohio, were destroyed and the shrubs badly disfigured.

DESCRIPTION OF ACHATODES ZEAE

THE EGG

The egg (fig. 2) is round, flattened dorso-ventrally, and about 0.61 mm in diameter by 0.28 mm in thickness. They are deposited usually in clusters or masses, but the individual eggs do not overlap. Each egg mass or cluster contains from 2 to 46 or more eggs, averaging 18. Occasionally 1 or 2 eggs were found separated by a short distance from the main egg mass. The egg masses vary in shape as well as size, sometimes exceeding 7.5 mm in length and 2.5 mm in width. When the eggs are deposited they are light yellow but shortly develop a shade of tan. The surface of the egg is rough or pebble-like, the center or polar area having a less roughened and more glossy appearance than its periphery. Shortly before hatching, the egg becomes much darker, owing to the appearance of the black head of the larva within.

FIGURE 2.—Eggs of *Achatodes zeae* on underside of outer bark of elder. The eggs are covered with the material used by the female for gluing them to the bark. ×8. Photo by Philip Luginbill

THE LARVA

Larva (fig. 3) when full grown about 1½ inches long by about one-eighth inch wide. Head, thoracic and anal shields, pinacula, spiracles, and thoracic legs are glossy black; body otherwise yellowish white; the markings very prominent.

No secondary hairs. Legs and prolegs normal. Crochets arranged in mesoseries, uniordinal. Anal shield strongly chitinized, very rugose, bearing three pairs or a row of prominent spines. Prothoracic shield broad, with a defined median line or band. Mesothoracic and metathoracic shields without setae, located near cephalic border and near meson, cephalad to setae 1^a and 1^b. Spiracles elongate oval; prothoracic spiracles larger than spiracles on abdominal segments 1–7; spiracles on abdominal segment 8 about the same size as spiracle on prothorax.

Body setae (fig. 4) moderately long; tubercles very pronounced, broadly chitinized; IV on abdominal segments 1–7 caudad of spiracle, caudo-ventrad on segment 8; prespiracular shield of prothorax nearly twice as large as spiracle and broadly ovate, bearing only two setae (IV–V), situated somewhat cephalo-ventrad of the spiracles: III on prothorax absent; group VI bisetose on prothorax but unisetose on mesothorax and metathorax; IV–V united on abdominal segment 9, not approximate to III; III cephalo-mesad of spiracle on abdominal segments 2–7, mesad on abdominal segment 1, and somewhat cephalo-dorsad on abdominal segment 8; III^a present on abdominal segments 1–8, before the spiracle on abdominal segments 2–7, more cephalo-dorsad of spiracle on abdominal segment 1, and cephalo-ventrad on abdominal segment 8; group VII trisetose on abdominal segments 2–6, unisetose on 7, 8, and 9, bisetose on abdominal segment 1; abdominal segment 9 bearing 6 prominent setae and 1 small one; II equidistant from I and III; II longer on segment 9 than on 1–8; setae on prothoracic shield as follows; I^a and I^b along frontal margin of the shield; I^c on ventral margin with II^c; distance separating I^b and I^c much less than distance separating II^b and II^c; I^c and II^c approximate; ninth abdominal segment bearing setae II, I, and III on a single pinaculum which forms a moderately broad shield extending to and almost touching the pinaculum of seta IV.

Head capsule spherical, slightly trapezoidal or broadly ovate in outline when viewed from above, a trifle wider than long; greatest width back of middle of

head, incision of dorsal hind margin pronounced but not real deep. Frons much longer than wide, not quite reaching to middle of head; adfrontal ridges parallel from lower limit of epistomal area to point of juncture of tentorial arms, thence converging to slightly curved lines to the longitudinal ridge;

FIGURE 3.—Larvae of *Achatodes zeae*: *a*, Entrance hole in a ground shoot of elder; *b*, *c*, *d*, larvae in tunnels. Note size of tunnels

longitudinal ridge slightly longer than frons; adfrontal sutures meeting longitudinal ridge slightly behind the middle of the head.

Ocelli six, normal; IV, V, and VI arranged in the form of a triangle; I, II, III, and IV equidistant from each other, but V and VI farther apart.

Epicranium with the normal number of primary setae and punctures and with three ultraposterior setae and one or two ultraposterior punctures. Anterior setae (A^1, A^2, A^3) in a right-angle triangle; A^2 smallest of the three; anterior puncture A^a ventrad of and slightly posterior to A^2. Posterior seta (P^1) slightly nearer to the longitudinal ridge than P^2, P^2 being posterior to and somewhat laterad of P^1; P^1 nearly on level with beginning of longitudinal ridge; posterior puncture (P^b) out of line with P^1 and P^2, slightly mesad, nearer to P^2 than to P^1; P^a antero-laterad of P^1, lying between P^1 and A^3. Lateral seta (L^1) postero-laterad of A^3, remote; lateral puncture (L^a) postero-dorsad of L^1, rather remote. Ocellar setae (O^1, O^2, O^3) well separated; O^1 approximate and slightly ventrad of ocellus IV, posterior to and slightly ventrad of ocellus I; O^3 remote from and posterior to ocellus VI; puncture O^a posterior and approximate to ocellus VI. Subocellar setae (SO^1, SO^2, SO^3) triangularly placed; SO^2 approximate to and postero-ventrad of ocellus V; puncture SO^a anterior to SO^3; SO^3 longest. Genal seta (G^1) postero-ventrad of O^3; puncture G^a dorsad of G^1.

Labrum normal, with usual number of setae and punctures; median incision moderately concave; setae (M^1, M^2, M^3) triangularly placed; M^1 nearer M^2 than M^2 is to M^3; M^2 posterior to M^3; puncture M^a approximate to and slightly laterad of M^1; M^2 longest of the three; L^a1 and L^a2 closely approximate; L^a3 remote from L^a2.

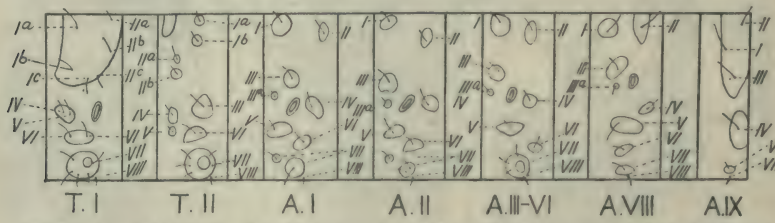


FIGURE 4.—Setal map of body segments of the spindle worm (*Achatodes zeae*)

Epipharyngeal shield not sharply defined, merging in a chitinized area on the central forward part of the labrum. Epipharyngeal setae slightly triangularly grouped behind anterior margin of epipharynx, moderately long, narrow, and equidistant.

Full-grown larva 29–34 mm long.

THE PUPA

After completing its growth the larva enters the pupal stage, or quiescent period. The pupa at first is a creamy white but soon changes to tan and later to a mahogany brown. (Fig. 6.) It measures 17 to 21 mm in length.

Pupa is moderately robust; abdominal segments gradually tapering; smooth except for some rugosity on cephalad margin on dorsum; wings extending to or nearly to the ventro-caudal margin of the fourth abdominal segment; cephalic end bluntly rounded, with two prominent knobs somewhat separated and dorsad of a prominent produced clypeus; epicranial suture present, represented by a curved line; vertex not distinct; labrum well developed, maxillary palpi absent; labial palpi moderately large; prothoracic legs extending three-fourths the length of the wings; prothoracic femora exposed; mesothoracic legs not extending to end of wings; maxillae extending to tips and the antennae nearly to tips of mesothoracic legs; metathoracic legs extending nearly to tips of wings; abdominal spiracles visible and pronounced; anal and genital openings slitlike in both sexes, ninth abdominal segment with four small stout dorsal spines; cremaster short, truncate, much broader in female than in male, and armed with four short heavy spines.

THE ADULT

The fore wings of the adult (fig. 5) are rust red, mottled with gray, with an irregular tawny spot near the tip. The hind wings are yellowish-gray with a faint discal mark. The head and thorax are

rust red, with raised tufts. The abdomen is pale brown, with a row of rust-red tufts on the dorsum. The adult varies in size, average specimens measuring about 1¼ inches across the wings.

FIGURE 5.—*Achatodes zeae:* A, Male moth; B, female moth. ×3

Hampson (*6, v. 9, p. 31*) describes the moth as follows:

Head and thorax fiery red mixed with pale yellow; palpi and sides of frons dark brown; tegulae with brown patches at sides; patagia with brown upper edges; pectus and legs dark brown, the tarsi ringed with white; abdomen dorsally fiery red, ventrally dark brown. Fore wing with the costal half grey-brown suffused with fiery red at base, in end of cell and at apex, the inner

half grey with some red suffusion at the base, middle, and termen, the veins with dark streaks; subbasal line indistinct, double, from costa to median nervure; antemedial line indistinct, double, waved, with black point on its inner edge at vein 1, nearly erect; claviform small, defined by brown; orbicular small, narrow, oblique, with brown center and grey annulus; reniform grey, its center defined by brown, rather oblique; an indistinct oblique waved red line from lower angle of cell to inner margin; postmedial line brown defined by grey on outer side, slightly bent outwards below costa, oblique to vein 6, then dentate and produced to a double series of black points on the veins, oblique below vein 4, some grey points beyond it on costa; subterminal line yellow, from costa to vein 6 and bent outwards at vein 7, then represented by a series of slight yellow spots on red streaks in the interspaces, somewhat excurved at middle; a terminal series of slight dark spots; cilia brown with series of slight whitish spots. Hind wing white suffused with grey-brown, especially on costal area, the terminal area rather whiter; an indistinct discoidal spot, curved postmedial line, and diffused subterminal line; a brown terminal line; cilia white tinged with brown toward apex; the underside white, the costal area tinged with red and irrorated with brown, a dark discoidal spot and rather diffused curved postmedial line.

Hab. Canada; U. S. A., Northern, Middle, Central, and Southern States. New York, Trenton Falls (*Doubleday*) 5 ♂ type *sandix*, Evans Center (*Grote*), 2♂, 1♀, Florida (*Doubleday*), 1♂, Colorado.

Exp. 28–34 mm.

EXPERIMENTAL METHODS

Experiments with the spindle worm were conducted in the field, and also in a wire cage 3 feet square and 3 feet high. Elder clumps were transplanted in the cage and developed satisfactorily. Two complete generations of the insect, or one each year, were reared under these conditions during the seasons of 1929 and 1930. Several infested thickets of elder, located within 25 yards of this cage, gave a fine comparison and an adequate check on cage conditions. Also, individual larvae were reared in green elder shoots kept in fresh water. Records of oviposition and longevity of adults were made under laboratory conditions.

LIFE HISTORY AND HABITS

THE MOTH

EMERGENCE

The moth (fig. 5) forces its way out of its pupal cell through a slightly protected exit, made for its escape by the larva before pupation. The pupa may be located in the green stalk in which it has fed as a larva, or as a free pupa on the surface of the ground, but more commonly in the dead, dry elder branches or stalks that are standing or lying on the ground under clumps of elder. At the time of emergence the wings are unexpanded, but within a short time they expand and become dry.

The moth is seldom observed, as it flies at dusk and during the night and hides among the weeds and at the base of the elder clumps during the day. Its rusty-gray color, blending well with that of the surrounding vegetation, probably aids in protecting it from its natural enemies.

MATING

Two pairs of moths in a wire-screen cage were mating at 7.30 p. m. on July 18. One pair remained thus 28 minutes and the other pair only 6 minutes. All these moths had emerged during the previous

night. No mating was noted during daylight hours, although several males and females were confined in a cage, and close observations were made to determine possible mating under daylight conditions.

OVIPOSITION

Oviposition was not actually observed. The eggs are placed and held in position with the aid of a sticky substance, between the outer and inner bark (fig. 6, *a*), or between the inner bark and the wood. In some instances the outer bark is loose and the inner bark is tightly attached to the wood, and under such conditions the moth deposits her eggs between the outer and inner barks. The greater part of the bark is tightly glued back to its original position—in fact, so tightly that the imprint of the eggs may be seen through the thin papery outer bark. Since eggs were repeatedly found at 9 p. m. on dead branches known to be free of eggs just prior to that hour, it was concluded that oviposition usually begins at dusk, although the actual deposition of such eggs was not observed.

The maximum number of eggs deposited by any one moth was 505, the minimum was 184, and the average for 10 moths was 309. The daily average oviposition for 10 moths was 76 eggs.

Hatching usually occurs during the morning hours. The peaks of the hatching period for 1929 and 1930 were April 20 and April 19, respectively. The larva emerges from the egg by chewing its way through the chorion. Most of the larvae emerge from the side of the eggs, rather than from the polar areas. The empty eggshell is transparent.

The duration of the egg stage is of great interest, as the insect spends nearly 10 months of the year in this stage. The eggs are deposited in July and hatch the following April.

THE LARVA

FEEDING HABITS

As soon as the larvae emerge, they immediately begin searching for food. They migrate from the egg masses to the new leaves that are just breaking forth from the new lateral shoots, or to the new shoots sprouting directly from the ground. As soon as the larvae reach these, they begin feeding in the leaf curls, where they are protected to a great extent from adverse weather conditions and from their natural enemies. Very little feeding occurs in cold weather, but during the warm portion of the day the larvae move about and feed. After feeding in the leaf curls for a few days they bore into the stems, where they continue to feed. They usually remain in the lateral shoots until the third or fourth stage is reached, when they migrate to the larger and more succulent ground shoots. However, if they first attack a ground shoot, they usually remain therein until their full larval development is completed. The ground shoots that sprout from the soil are large and grow very rapidly.

The larvae (fig. 3) feed up and down the interior of the shoots—usually up from the point of entrance—eventually producing a tunnel or burrow that extends from a point an inch or two above the ground to the apex of the shoot. The tunnel is rather small at first, but as the larva increases in size, it is enlarged until the pithy portion of the stem is entirely consumed. Two and three larvae have been

found in one shoot. The frass is ejected through the entrance hole, and an accumulation of this material appears at the base of the shoot. Small quantities of frass may be found in the tunnel near the base of the shoot, and usually some of the frass adheres to the

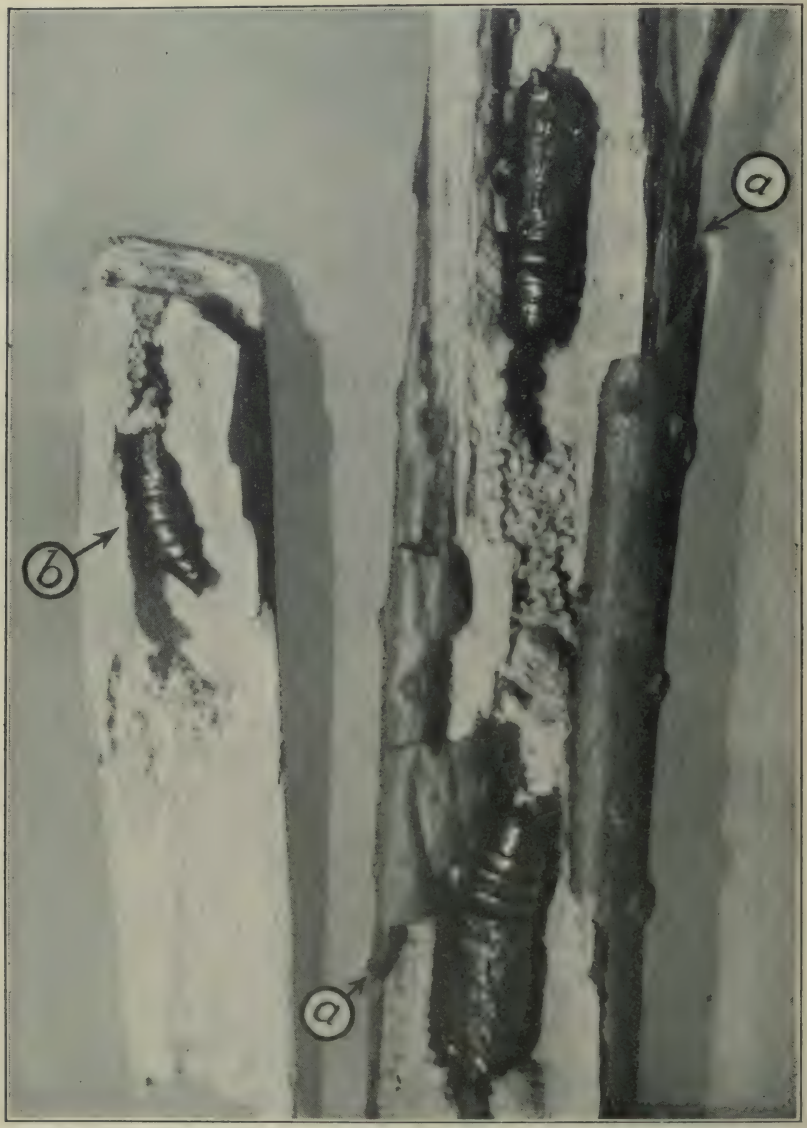


FIGURE 6.—The spindle worm (*Achatodes zeae*): *a*, Eggs laid under loose bark of elder; *b*, pupa in cell. ×3

outside of the entrance hole, particularly during the earlier part of the season.

No cannibalism was observed by the writer. Several third-stage and fourth-stage larvae were confined together overnight in a small

wire container, but no cannibalistic action was observed under these conditions or during the progress of numerous field observations.

MOLTS

The larvae cease feeding just prior to molting and appear inactive, or lethargic, for several hours. The skin ruptures directly back of the head, and as a result of a series of wriggles, contractions, and expansions the molted skin is worked back over the body. The head capsule may be cast before the skin or afterwards but is usually cast during the process of molting. Certain of the larvae were seen scratching their heads back and forth against some object, attempting to free themselves of the old head capsules. Under cage and field conditions a larva occasionally fails in this attempt and dies from starvation.

The newly molted larvae are white. The head and chitinous markings are at first white but turn grayish and finally black. The entire process of ecdysis requires from 10 to 30 seconds. Within a few hours the larvae are again feeding and very active.

Ordinarily five molts occur, but certain individual larvae developed only four.

LARVAL INSTARS

First instar.—Segments mottled with reddish, sutures yellowish white. Cervical and anal shields brownish black. Setae moderately long. Spines on anal shield absent. Seta III[a] absent. Length of larva 1.95 mm; width of head 0.29 mm; length of cervical shield 0.319 mm; width of cervical shield 0.087 mm; length of anal shield 0.174 mm; width of anal shield 0.116 mm. Spiracles circular.

Second instar.—Tubercles more prominent, brownish black; body greenish white. Head and cervical and anal shields black. Spines on anal shield showing slightly. Spiracles circular. Length of larva 3.59 mm; width of head 0.522 mm. III[a] present.

Third instar.—Body greenish white, tubercles black. III[a] more prominent. Spines more prominent. Spiracles slightly ovate. Length of larva 9.48 mm; width of head 1.14 mm.

Fourth instar.—Body white, tubercles black. Spiracles ovate. Length of larva 17.59 mm; width of head 1.68 mm.

Fifth instar.—Body yellowish white, very much like the sixth-stage larva. Length of larva 25.50 mm; width of head 2.28 mm.

Sixth instar.—Body yellowish to dirty white. Tubercles prominent, anal shield dull black, cervical shield and head shiny black, as are the other tubercles. Length of larva 34.75 mm. Width of larva 4.1 mm; width of head 2.55 mm.

DURATION OF LARVAL PERIOD

The duration of the larval period, as in other insects, is pronouncedly influenced by the prevailing meteorological conditions and the food supply. The first molt occurs from 4 to 7 days after the larva hatches from the egg. At this time the larva is from 2 to 4 mm in length. From 3 to 7 days are spent in the second stadium, and during this period the larva attains a length of from 5 to 9 mm. The third stadium occupies from 3 to 8 days, the length of the larva of this instar ranging from 10 to 17 mm. The fourth stadium is from 4 to 8 days in duration, the larva attaining a length of 18 to 24 mm. From 7 to 16 days are spent in the fifth stadium, the larva attaining a length of 25 to 30 mm; while the sixth and final stadium lasts from 14 to 22 days, the larva attaining a length of 30 to 35 mm.

PUPAL CELLS

The full-grown larva constructs a cavity or cell in preparation for pupation. This cell (fig. 6, *b*) is made infrequently in a green stalk but more commonly in old, dry elder branches possessing soft pithy centers. The cell is usually composed of frass and silk, and the orifice for the exit of the moth is filled lightly with the same material. Even though this material functions as a protection against natural enemies, the nature of its construction is such that the emerging moth can escape.

In a collection of 100 pupae, 93 were found in old dead branches and stalks, 5 were found in green shoots that had been severely attacked by the larvae, and 2 were on the ground without any protection

PREPUPA

After the cell is completed, the larva becomes quiet and shrinks in size, gradually becoming inactive and helpless. After a few days in this condition the larval skin is cast, and the pupa is formed.

PUPA

When first exposed the pupa (fig. 6, *b*) is creamy white, very delicate, and easily injured. It gradually hardens and assumes a mahogany-brown coloration, which in turn becomes darker just prior to the emergence of the moth. Except for spasmodic wriggling movements when disturbed, the pupa is inactive. In the 10 specimens under observation the duration of the pupal period ranged from 14 to 26 days, with an average of 18.3 days.

LONGEVITY OF ADULTS

Adults were observed to live from 2 to 11 days under cage conditions, with an average of 5 days for the 10 specimens under observation. Various flowers, and also a sugar-water solution, were placed in the cage for food.

SEASONAL DEVELOPMENT

The spindle worm passes nearly 10 months of the year (from July to April) in the egg stage. (Fig. 7.) The duration of the larval stage is approximately 58 days, and that of the pupal stage approximately 18 days. The adult stage, under cage conditions, lasts approximately five days.

On April 18, 1929, newly hatched larvae were found in the leaf curls. On April 17, 1930, the first eggs hatched. The first sixth-stage larva was found on May 22, 1929, and the first full-grown larva on June 7, 1929. In 1930 the first sixth-stage larva was observed on May 21, and the first full-grown larva on July 4. In 1929 pupae were first observed on June 15, and in 1930 on June 13. In 1929 moths appeared under cage conditions on July 5, and in 1930 on June 22.

C. E. Smith sent the writer a collection of larvae of *A. zeae* which he had collected in elder at Baton Rouge, La., on March 12, 1931, and upon arrival at Toledo, Ohio, on March 15, they were in the second and third stadia. This collection shows that the date of hatching in Louisiana is approximately a month and a half earlier than in northern Ohio.

ARTIFICIAL DISSEMINATION

Dissemination of the spindle worm, at least in important numbers, by the aid of man seems rather questionable, as the elder growth on which the eggs are deposited or in which the pupae are imbedded has no appreciable economic value. At the time of year when the elderberries are harvested, the insect has deserted the green stems on which the berries are borne. The only possible avenue of artificial dissemination would appear to be in the shipping of ornamental varieties of elder from nurseries. However, plants intended for shipment from nurseries are carefully pruned and the old, dead wood ordinarily bearing the eggs is removed before shipment.

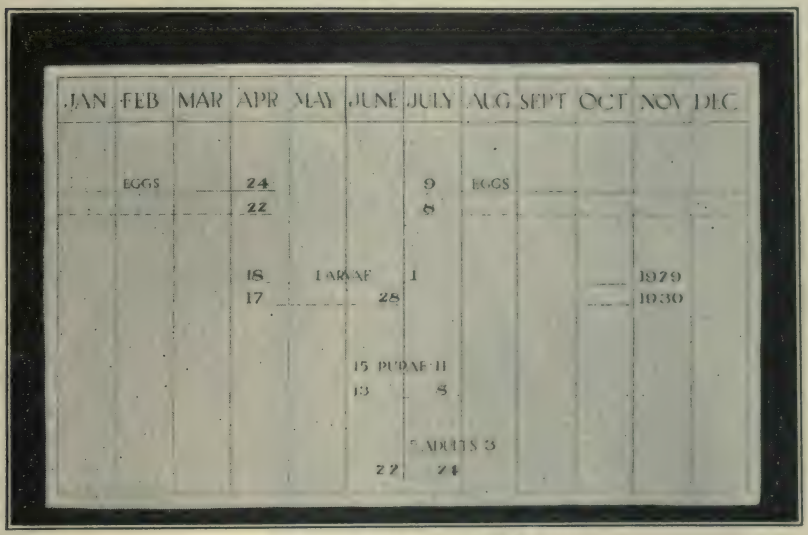


FIGURE 7.—Seasonal history of *Achatodes zeae*

NATURAL DISSEMINATION

As the moths of the spindle worm are active only after dusk, it is difficult to determine the details of their flight habits, and, particularly, their powers of flight.

It has been observed that several isolated patches of elder were infested, even though several miles away from other elder, thus indicating that the moths are able to fly for some distance. The robust structure of the moth also supports this theory.

NATURAL CONTROL

PARASITES

Several species of hymenopterous and dipterous parasites were found attacking *Achatodes zeae*. A small hymenopterous parasite, *Microplitis gortynae* Riley (fig. 8), has been found to be the most numerous of this group. Parasitism by this species attained a maximum of 11 per cent, according to Balduf (*1*), who determined this parasite species for the writer, and who records it as being numerous in other localities. He found the first mass of cocoons of *M. gortynae*

of the season of 1929 on June 20, at Monroe, Mich. On June 20, 1929, D. J. Caffrey found a mass of these cocoons at Mentor, Ohio. The writer observed the first mass of these cocoons at Bono, Ohio, on July 1, 1929. On June 14, 1930, masses of cocoons of this parasite were found at Bono.

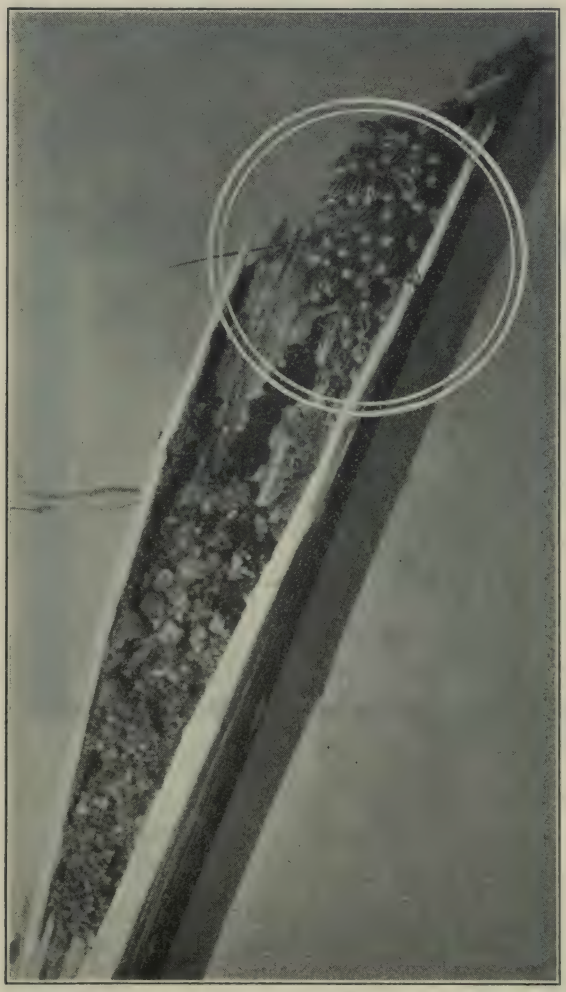


FIGURE 8.—Cocoons of *Microplitis gortynae* in tunnel in elder. Note host remains (*Achatodes zeae*) in front of cocoons. ×3

M. gortynae issues from the full-grown larva of *Achatodes zeae* and remains closely adjacent thereto. The parasite pupates and overwinters within its cocoon, emerging the following spring. The cocoons are fluted and dirty white. The number of individual parasites issuing from each host larva ranges from 10 to 38.

Another hymenopterous parasite, *Microbracon lutus* (Prov.), was recorded by the writer as parasitizing 3 per cent of the spindleworm larvae during 1929 in the Bono, Ohio, district. This species was determined by Balduf, who found it present June 20, 1929, at Monroe, Mich. *M. lutus* was first observed at Bono by the writer on June 1, 1929. This parasite is gregarious and the masses of cocoons are found closely adjacent to the host remains. The cocoons are chocolate brown and are glued closely together. The number of individuals issuing from one host larva ranges from 4 to 12. This parasite overwinters in the cocoon stage, in a similar manner to *Microplitis gortynae*.

Two specimens of the large ichneumonid *Amblyteles sclestus* (Cress.)[8] were reared from a collection of 100 pupae of *Achatodes zeae*. They issued on July 11 and 17, 1929.

[8] Determined by C. F. W. Muesebeck, of the U. S. Bureau of Entomology.

Several specimens of *Miotropis clisiocampae* Ashm. issued from one pupa of *Achatodes zeae*. The specimens were determined by Muesebeck, who stated in a memorandum at the time that "this species occasionally acts as a primary parasite of various lepidopterous larvae, but under certain conditions may also become a secondary parasite." The writer also found this species attacking cocoons of *Microplitis gortynae*.

On July 19, 1929, one specimen of *Phytodietus pulcherrimus* Cress.[8] was found by Caffrey and the writer near the remains of a larva of *A. zeae* in an elder shoot. It was in the pupal stage and failed to issue.

One cocoon of *Epiurus pterophori* (Ashm.)[9] was found on May 28, 1930, at Bono, Ohio. The adult issued on June 12, 1930.

One cocoon of *Sagaritis oxylus* Cress.[9] was found on May 28, 1930, from which the adult issued on the afternoon of the same day.

W. V. Balduf found a tachinid puparium, determined as *Masicera* sp. (probably *myoidea* Desv.)[10] as a coparasite with *M. gortynae* at Monroe, Mich. Both species developed from one larva of *A. zeae*.

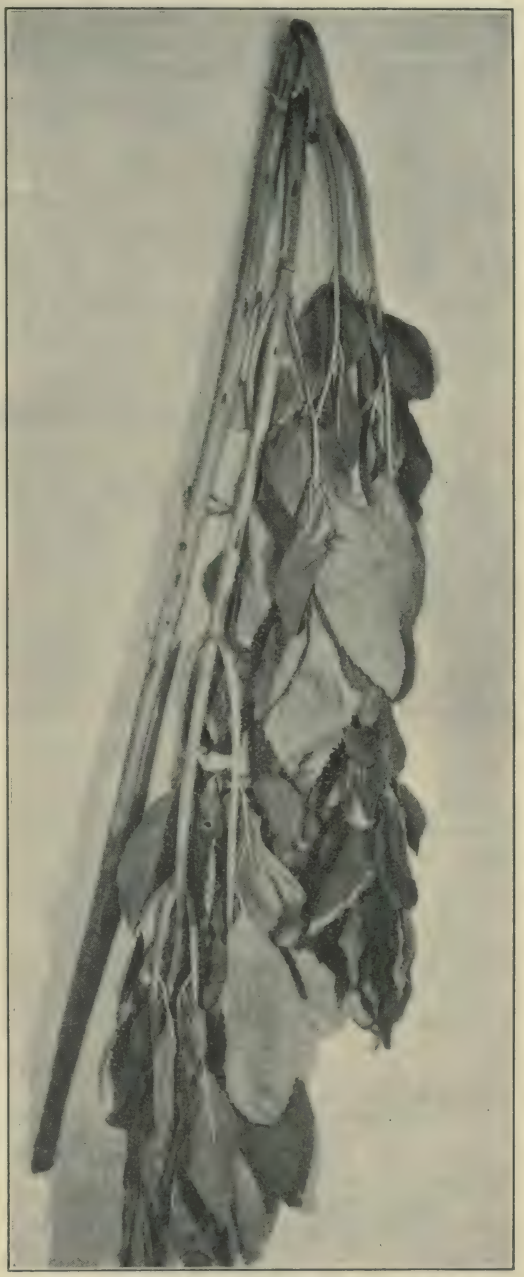


FIGURE 9.—Elder shoots, showing punctures made by birds to obtain larvae of *Achatodes zeae*

[8] Determined by C. F. W. Muesebeck, of the U. S. Bureau of Entomology.
[9] Determined by R. A. Cushman, of the U. S. Bureau of Entomology.
[10] Determined by R. T. Webber, of the U. S. Bureau of Entomology.

Another tachinid, *Nemorilla floralis* Fall.,[10] was reared from a larva of *A. zeae* at Baton Rouge, La., by C. E. Smith.

No egg parasites were reared.

BIRDS AND RODENTS

The northern downy woodpecker (*Dryobates pubescens medianus* (Swains.)) was observed attacking young elder shoots in search of spindle-worm larvae. An examination of these green shoots disclosed that the bird had removed the larvae. Several clumps of elder in various localities showed distinct signs of attack by birds. (Fig. 9.)

Several clumps of elder in widely separated localities exhibited signs of attack by rodents that apparently removed the spindle-worm larvae from the green shoots.

ARTIFICIAL CONTROL

As the spindle worm spends such a large proportion of its life in the egg stage, and as the eggs are deposited under the bark of old, dead elder branches and stalks, its control is relatively easy to accomplish. None of the moths overwinter to deposit eggs for a new generation, therefore the species can be controlled by removing from and about the elder clumps all dead wood on which the overwintering eggs have been deposited, raking it into a pile, and burning it during the fall, winter, or early spring to destroy the eggs. Actual field tests have demonstrated the efficiency of this method of control, and it has proved to be so practical that no other methods were tried.

SUMMARY

The spindle worm, or elder borer (*Achatodes zeae* Harr.) sometimes seriously injures elder and very rarely injures corn, but this insect can not be considered of much economic importance.

The larval, or injurious stage of the insect, is short in duration and is usually confined to uneconomic plants.

Natural control by several species of parasites and by birds and rodents usually holds this insect in check.

The eggs are easily destroyed during the fall and winter months by burning the old, dead elder wood to which they are attached.

LITERATURE CITED

(1) BALDUF, W. V.
1929. BIONOMIC NOTES ON SOME PARASITES OF ACHATODES ZEÆ HARRIS (NOCTUIDÆ, LEP.) AND PHLYCTÆNIA TERTIALIS (GUEN.) (PYRALIDÆ, LEP.). Ohio Jour. Sci. 29: 218–242.

(2) BREAKEY, E. P.
1930. CONTRIBUTION TO A KNOWLEDGE OF THE SPINDLE WORM ACHATODES ZEÆ (HARRIS), (LEPIDOPTERA, NOCTUIDÆ). Ann. Ent. Soc. Amer. 23: 175–191, illus.

(3) DYAR, H. G., FERNALD, C. H., HULST, G. D., and BUSCK, A.
1902. A LIST OF NORTH AMERICAN LEPIDOPTERA AND KEY TO THE LITERATURE OF THIS ORDER OF INSECTS. U. S. Natl. Mus. Bul. 52, 723 p.

(4) ELLIS, W. O.
1925. SOME LEPIDOPTEROUS LARVÆ RESEMBLING THE EUROPEAN CORN RORER. Jour. Agr. Research 30: 777–792, illus.

[10] Determined by R. T. Webber, of the U. S. Bureau of Entomology.

(5) FORBES, S. A.
1905. A MONOGRAPH OF INSECTS INJURIOUS TO INDIAN CORN. PART II. Rpt. State Ent. Ill. 23, 273 p., illus.
(6) HAMPSON, SIR G. F.
1910. CATALOGUE OF THE NOCTUIDÆ IN THE COLLECTION OF THE BRITISH MUSEUM. 552 p., illus. *In* Catalogue of the Lepidoptera Phalænæ in the British Museum, v. 9, illus. London.
(7) HARRIS, T. W.
1841. A REPORT ON THE INSECTS OF MASSACHUSETTS INJURIOUS TO VEGETATION. 459 p. Cambridge.
(8) MATHEWS, F. S.
1915. FIELD BOOK OF AMERICAN TREES AND SHRUBS; A CONCISE DESCRIPTION OF THE CHARACTER AND COLOR OF SPECIES COMMON THROUGHOUT THE UNITED STATES, TOGETHER WITH MAPS SHOWING THEIR GENERAL DISTRIBUTION. 465 p., illus. New York and London.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Chief.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Entomology	C. L. MARLATT, *Chief.*
Division of Cereal and Forage Insects	W. H. LARRIMER, *Principal Entomologist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - Price 5 cents

Technical Bulletin No. 344 January, 1933

PETROGRAPHIC METHODS FOR SOIL LABORATORIES

BY

W. H. FRY

Soil Petrographer, Division of Soil Chemistry and Physics
Soil Investigations, Bureau of Chemistry and Soils

United States Department of Agriculture, Washington, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - - - - - - - Price 10 cen

IN MEMORIAM

Work on the galley proof of this bulletin was completed by the author on the morning of his death, December 27, 1932. It seems fitting to preface this publication, which the author considered his best effort, with a brief account of his activities.

Mr. Fry became associated with the Bureau of Soils on December 15, 1911, and, except for a period of three months in 1922, continued this association until his death. He was a native of North Carolina and graduated from the university of that State in 1910. During his undergraduate years and for a year thereafter he served as assistant and instructor in the department of geology in that university. He published several short articles previous to coming to Washington and since that time has published, either alone or as associate author, some 35 contributions to soil literature. These contributions center around the detection and estimation of soil minerals by petrographic methods, and his name is indissolubly associated with the great advance in the knowledge of soil colloids which has occurred in recent years. In the progress of his work he developed a technic which is unique. The work he has been able to do has had a marked effect on the trend of investigations within the bureau with respect to both soil chemistry and soil physics. Besides his research, his services were frequently required by others in connection with their own work, and it is probable that but few names have appeared so frequently as a contributor to papers not related directly to his work. He was also called on to identify a wide range of miscellaneous materials which came to the bureau and in this line he developed great skill. A very large number of persons, to whom his name is entirely unknown, have been aided by his expert assistance. Personally he was affable, extremely modest, of the strictest personal and scientific integrity, and his associates will long lament his untimely death.

TECHNICAL BULLETIN No. 344 JANUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

PETROGRAPHIC METHODS FOR SOIL LABORATORIES

By W. H. FRY

Soil Petrographer, Division of Soil Chemistry and Physics, Soil Investigations, Bureau of Chemistry and Soils

CONTENTS

	Page
Introduction	1
Crystal form	4
Fundamental properties of light	6
Polarized light	9
Double refraction	10
Becke lines	13
Interference of light	14
The petrographic microscope and accessories	16
Mechanical parts	16
Optical system	18
Calibration and measurements	25
Optical methods	33
Immersion media	33
Determination of refractive index by Becke line	34
Determination of two indices of refraction	36
Determination of three indices of refraction	37
Interference figures	39
Optical character	45
Optic-axial angle	48
Dispersion of optic axes	50
Measurement of double refraction (birefringence)	53
Extinction angles	58
Optical methods—Continued.	Page
Sign of elongation	61
Color of crystals	61
Pleochroism	62
Orientation	63
Application of methods	63
Pure substances	63
Identification of minerals in soils	64
Percentage estimation of constituents in a mixture (mechanical analysis)	71
Differentiation of soil colloids from soil crystalline material	76
Soil organic matter and residue of organisms	78
Shape of particles	79
Residues from the evaporation of soil solutions	81
Vertical illumination	82
Particle surfaces	82
Soil structure	83
Ultramicroscopes	84
Fertilizer materials	85
Miscellaneous materials	86
Inspection of samples for purity	86
Phase-rule problems	87
Appendix	89
Literature cited	95

INTRODUCTION

For many years, almost since the beginning of microscopy, the ordinary microscope has been used for the observation of crystals too small to be otherwise observed. Certain obvious similarities and dissimilarities between different crystalline substances were early noted and were used as confirmatory methods of identification. For example, the cubes of sodium chloride were seen to be identical in appearance with the cubes of potassium chloride, but both were found to be utterly dissimilar to the monoclinic, frequently twinned, crystals of gypsum. Here, then, were two substances which could not be distinguished from each other by simple observation, no matter how perfect the microscope might be as a magnifying instrument, whereas either could be instantly distinguished from the third substance even with a very crude microscope. In process of time such

cases multiplied, and the distinguishing characteristics of the various crystals were studied with greater attention to detail. These studies brought to light a wealth of crystallographic information, some of which extended the lists of definitely identifiable substances, but much of which simply added new members to already large groups of observationally indistinguishable crystals.

Such a result was inevitable. There are only six major crystalline systems, to some one of which each crystal must belong. The subdivisions of these six systems give a somewhat larger number of groups, but at best there is a very large number of crystals falling in each group and therefore having the same general appearance, although they may be completely unlike chemically. Matters are further complicated by the fact that a given substance may, under certain conditions, crystallize in one subdivision of a system, and under other conditions in some other subdivision. For instance, both sodium chloride and potassium alum crystallize in the isometric system, but both may appear as cubes or as octahedrons. It is thus evident that a given crystal not only does not necessarily show definitely diagnostic characteristics on simple observation, but also that it could not be expected to do so.

Common sense supplied a solution to the problem by the simple elimination of all substances except those which could be reasonably expected to crystallize from a given solution. In cases where it was known what could crystallize out of a given solution and where these possible crystals were sufficiently different, identification by appearance could readily be made, if the crystals came down in sufficiently perfect and characteristic form. But they did not always do this. This method is only infrequently applicable, but when it is applicable it is capable of giving very good results if used with judgment.

The methods of qualitative chemical analysis under the microscope have abundantly proved their value but they have severe limitations. (1) The substance to be analyzed under the microscope must be fairly readily soluble without too much preliminary treatment. This practically eliminates most of the silicate minerals. (2) Some of the methods depend on the visual recognition of crystals formed by the substance under analysis and the reagents applied to it. All that has been said as to the uncertainty of crystal determination by ordinary observation applies here with perhaps added force. (3) Microchemical tests on mixed substances leave a degree of uncertainty as regards the composition of any particular crystalline component of the mixture. (4) Microchemical tests do not distinguish between different allotropic forms of the same substance, between different hydrates, or between salts which have qualitatively the same but quantitatively different compositions.

Geologists were early confronted by the problem of identification of crystalline substances in rocks, a problem which combined almost all the difficulties outlined above. The mineral constituents of a granite, for example, usually show no external crystal form whatever and can not therefore be identified even tentatively by their forms. Most microchemical tests are altogether inapplicable. Resort was had, of necessity, to methods based on physical properties which were capable of showing internal crystalline structure regardless of whether or not this internal structure was manifested by external form.

As it happened, the optical properties were particularly well adapted for this purpose. Methods and apparatus were devised and improved, and a vast literature on the microscopic constitution and structure of rocks was rapidly built up. This new field was sufficient to occupy the attention of geologists and mineralogists for many years, and consequently very little attention was paid by them to artificial crystals obtained in the laboratory. Gradually, however, there appeared a small amount of data on the optics of artificial crystals, and finally the exigencies of certain largely chemical problems, notably those of cement, demanded the accumulation and application of definite data in the identification of specific artificial compounds. It was found that artificial crystals were just as susceptible, and perhaps more so, on account of their purity, to optical identification as were the natural crystalline minerals. Methods predominantly suited to rock sections were modified to apply more accurately and conveniently to loose crystals. Thus optical crystallography ceased to be merely a means for rock study and broadened out into its rightful place of a physical method applicable, to some extent at least, in most studies where crystalline material is or may be present.

Aside from the vast field of rock and mineral study, successful application has been made of optical crystallography in the identification of sugars, alkaloids (*18*),[1] cement constituents, fertilizer materials (*5*), mixed salts crystallizing from brines and from soil extracts (*1*), dyes, solid phases obtained in various phase-rule studies, organic substances obtained from the brain, from soils, and from plants (*3*), silicate melts, and various other miscellaneous materials (*8*). There has even been some slight progress made in the application of the methods to certain so-called colloidal aggregates (*6*).

But the success of the methods should not blind one to the fact that optical crystallographical methods, in common with all other methods, have their limitations. Although there are real exceptions, as in the determination of the refraction indices of glasses, and presumably apparent exceptions, as in the study of colloidal aggregates, it may be said in general that optical crystallography applies only to the nonopaque crystals. The opaque crystals have their own special technic, which can be found in any text on metallography (*15*). Furthermore, the crystals to be identified must be of a size greater than submicroscopic and must have a real crystalline structure and not merely the incipient crystallinity of the so-called "skeleton crystals." These skeleton crystals have a particularly attractive appearance when seen in clusters sticking to the sides of a beaker or test tube, and for this reason have a tendency to tempt one to much futile work which could be successfully and easily accomplished if the crystals were given sufficient time for growth. Skeleton crystals are frequently mistaken for completed forms by workers without considerable crystallographic experience.

The above limitations still leave a vast field of literally hundreds of thousands of compounds open to the study of their optical crystallography. The optics of the naturally occurring minerals have been reasonably well worked out, and the data are readily avail-

[1] Italic numbers in parentheses refer to Literature Cited, p. 95.

able. But the same can be said of only a comparatively small number of the total possible artificial compounds. This lack of data is a continually recurring source of embarrassment, but is becoming less so as more data are being gradually accumulated and compiled.

It is the purpose of this publication to present in very brief form the crystallographic, optical, and manipulative principles absolutely necessary for the petrographic identification of crystals. Only so much is included as seems indispensable. All mathematical treatment has been eliminated so far as possible without loss of clarity. This has been done in spite of the fact that fundamentally both crystallography and optics are almost wholly mathematical sciences. For information beyond the minimum given in this bulletin the reader is referred to the standard texts (*2*, *4*, *7*, *13*, *16*, *20*).

CRYSTAL FORM

The primary characteristic of a crystal is its actual or potential geometrical form that determines to which of the six crystallographic systems it belongs. These six systems are based on purely geometrical principles and, in general, but not in detail, it may be said that the optics of a given crystal depend on the system to which it belongs. A complete crystallographic description of the geometrical properties of a given crystal would indicate to the experienced worker whether the crystal was isotropic or anisotropic and, if the latter, whether it was optically uniaxial or biaxial, but it would give no indication as to the refractive indices, the value of the double refraction, the size of the optic axial angle, the dispersion, or the optical character. On the other hand, a complete optical description of a crystal might fail to give any data which would definitely establish its system, for example, it is usually impossible to distinguish between a tetragonal and a hexagonal crystal by optics alone. Furthermore, the optical data never furnish information as to external form. Optically there is no difference between a 6-sided cube, an 8-sided octahedron, and a 12-sided dodecahedron, but the optics would establish the fact that each belonged to the isometric system. Crystallography and optical crystallography are thus mutually related and to a certain extent mutually dependent, but neither is completely expressible in terms of the other. Both should therefore be used to the greatest extent possible.

The six crystallographic systems are the isometric, the tetragonal, the hexagonal, the orthorhombic, the monoclinic, and the triclinic, and they are defined as follows:

The isometric system has three equal axes all at right angles to each other. If each face of the crystal is parallel to two of the axes and at right angles to the third, the form is that of a cube. If each face cuts all three axes at unit distance from the center, the form would be that of an octahedron. There are many other forms, all depending on the relationship between the faces and the axes.

The tetragonal system has two equal axes and a third either longer or shorter than the first two, all at right angles to each other.

The hexagonal system has three equal axes in one plane at 60° from each other and a fourth axis, either longer or shorter and at right angles to the plane of the first three.

The orthorhombic system has three unequal axes all at right angles to each other.

The monoclinic system has three unequal axes, any two of which are at right angles to each other and the third inclined to the plane of the other two.

The triclinic system has three unequal axes all inclined to each other.

In the isometric system, since all the axes are equal, it is a matter of indifference how the axes are denominated. If a cube is set up so that the observer looks squarely into one face, he can readily conceive of three equal axes at right angles intersecting each other in the center of the cube and each one passing through the centers of two opposite faces. That axis pointing toward the observer may be labeled a or $\bar{a}$, depending on whether he is considering it as directed from the center of the cube toward the front or from the center toward the rear. Similarly, he can label the horizontal axis at right angles to the first as b or $\bar{b}$, depending on whether its direction is to the right or to the left of the cube center. The vertical axis can be labeled c or $\bar{c}$, depending on whether its direction is considered as up or down from the center. The front face intersects the a axis at unit distance and is parallel to the other two axes, that is, does not intersect them at all. This face may therefore be labeled (100). The left side face intersects the $\bar{b}$ at unit distance and is parallel to the other two axes. This face may be labeled $(0\bar{1}0)$, and so on for all the other faces. An octahedral face intersects all three axes at unit distance and therefore has the symbol (111), $(\bar{1}11)$, or some other, depending on the location of the particular face.

In the tetragonal system, the unequal axis is always the vertical, that is, the c axis. The unit distance on the c axis is not the same unit as that of the a and b axes, but, with this difference understood, the symbols for the different faces are obtained as in the isometric system.

In the hexagonal system the unequal axis is the c axis, as in the tetragonal system. But since there are four axes altogether, there are four numbers in each face symbol. For example, a basal plane is parallel to all three horizontal axes, but intersects the vertical axis. The symbol is therefore (0001) or $(000\bar{1})$.

In the orthorhombic system the shorter diagonal axis is denominated a, the longer axis b, and the vertical axis c. The face symbols are derived as in the other systems.

In the monoclinic system b is identified as that axis lying perpendicular to the plane of symmetry of the crystal; a and c lie in the plane of symmetry and are inclined to each other. The face symbols are derived as in the other systems.

In the triclinic system a is usually the shorter diagonal axis and b the longer diagonal axis. There are cases, however, in which this is reversed. c, of course, is the third axis. The face symbols are derived as in the other systems. The angle β is the angle between a and c.

The preceding remarks on crystallography are intended purely as a species of definition of terms. The reader is referred to any good text on crystallography for further information (*4*, *13*, *16*).

FUNDAMENTAL PROPERTIES OF LIGHT

For practical purposes light can be defined as radiant energy which affects our organs of vision. We are ignorant of its fundamental character, but its phenomena can be explained sufficiently by either of two theories: (1) That it is a wave motion originating from some luminous source of energy and propagated in an all-pervading ether, or (2) that it is a stream of actual quanta of luminous energy, coming from the source to the observer. The present tendency is to give preference to the second theory, but, so far as applied optical crystallography is concerned, both serve equally well. The wave-motion theory is the one most commonly taught and understood, and, up to the present, all texts of optical crystallography have been written in terms of this theory. For these reasons light will be here considered as simply a transmission of radiant energy by wave motion in an ether, and all questions of quanta will be ignored.

Regardless of theory, there are several fundamental facts concerning the propagation of light which can be verified easily, even by the simplest sort of observation:

(1) Light, in a homogeneous medium, travels in straight lines. Observations on shadows or, better still, observations on images formed by pinhole cameras, as explained in any textbook on physics (*17*), will give an adequate concept of this fact.

(2) Light traveling in one medium is at least partly reflected back into this medium on striking another medium of optical density different from the first. Mirrors give the best example of this fact.

(3) The path of light, passing from one medium into another medium of different optical density, at any angle other than a right angle, is bent or refracted.

(4) Ordinary so-called white light is made up of various colors which can be separated into a spectrum with red at one extreme and violet at the other. Any transparent prism will demonstrate this fact.

(5) Light will pass through certain substances, which are spoken of as transparent or translucent, and will not pass through certain other substances which are spoken of as opaque. Glass is an example of transparent substances and sheet iron of opaque substances. Between these two extremes there are all gradations. In other words, different substances absorb transmitted light in different degrees; and, usually, with white light, absorb certain colors more or less than other colors.

(6) Under certain conditions light rays can be made to interfere so as to produce darkness.

If a light ray traveling through a homogeneous medium along the line and in the direction *ns* (fig. 1) strikes a medium of different optical density at *s* at right angles, part of the light enters the second medium and is absorbed or transmitted, as the case may be, but part is reflected back along its original path but in the opposite direction; that is, along *sn*. Thus, when the angle of incidence, *i*, is 0°, the path of incidence and the path of reflection are the same, although the directions are opposite. It might be said that the path has been turned through an angle of 180°.

If the ray travels along some line *as*, making angle *i* greater than 0° but less than 90°, then the ray, on striking the second medium, is

reflected back into the first medium in such a manner that angle i=angle e. We therefore have the law that, in a homogeneous medium, the angle of incidence is equal to the angle of reflection.

At a certain angle i, which varies with the nature of the two media but which is constant for any two substances at a given temperature, none of the light enters the second medium, but the entire ray is reflected back into the first medium. This angle is known as the critical angle for the two substances. For angles of incidence, therefore, between 0° and the critical angle, only part of the light is reflected, the other part entering the second medium. At angles equal to or greater than the critical angle, but less than 90°, all the light is reflected back into the first medium, none of it entering the second. The maximum of light enters the second medium at 0° incidence, and the amount decreases regularly until it reaches zero at the critical angle.

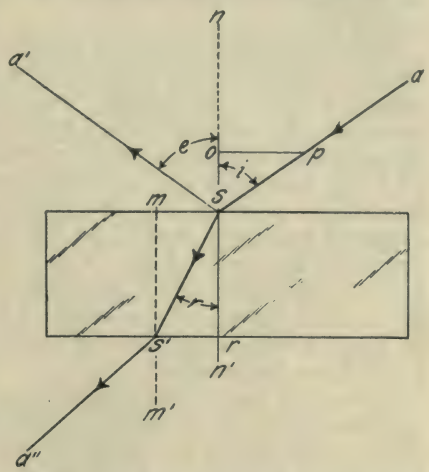


FIGURE 1.—Refraction of light and refractive index relationships

The light which enters the second medium, is, as has been stated, either absorbed, transmitted, or partly absorbed and partly transmitted. Assuming, for the sake of simplicity, that it has all been transmitted, or that the second medium is perfectly transparent, the following relations hold:

The ray as, on entering the second medium, is bent or refracted from its original direction into some new direction ss'. If nn' is the normal to the surface of the second medium at s, then the angle of incidence, i, has some value other than the angle of refraction, r.

Taking $sp=ss'$

$$\text{then } \sin i=\frac{op}{sp}$$

$$\text{and } \sin r=\frac{s'r}{ss'}=\frac{s'r}{sp}$$

Therefore

$$\frac{\sin i}{\sin r}=\frac{op}{sp}\cdot\frac{sp}{s'r}=\frac{op}{s'r}$$

The value of $\frac{op}{s'r}$ is specific for every known pair of media. Air is usually taken as the first medium and therefore the value $\frac{op}{s'r}$ becomes a constant for any individual substance taken as the second medium.

We may therefore write

$$n=\frac{\sin i}{\sin r}$$

where the value n denotes refractive index. Hence, in relationship to air as a standard, every known substance has a particular refrac-

tive index, n, which serves to distinguish it from most other substances. Of course there are some substances of which the indices of refraction are so nearly the same as to make their differentiation impracticable by refractive-index measurements alone. But even in such cases, the refractive index differentiates a small group of substances from a vast number of other substances; and the members of the small group can usually be differentiated from each other by further optical tests. At worst, it is much better to be able to determine that a particular substance is one of two or three, or even a dozen, substances than to be totally ignorant of even what it might be.

In the diagram (fig. 1) angle r is shown as less than angle i. This is the condition that obtains when the refractive index of the second medium is greater than the refractive index of the first medium. If the direction of the light ray were reversed, the angle of incidence, i, and the angle of refraction, r, would be interchanged. The ray traveling in the second medium from s' to s would be refracted on passing into the first medium in a direction sa and the angle of incidence would be less than the angle of refraction. All this may be summed up in the statement that, on passing from a medium of lesser into a medium of greater index of refraction, the ray is bent toward the normal; whereas, on passing from a medium of greater into a medium of lesser refractive index, the ray is bent away from the normal.

If the ray passes through the second medium and reenters the first medium again at the point s', the phenomena are the same as at the point s, except in a reverse direction. Therefore the path $s'a''$ is parallel to the path as. Thus, the aggregate effect is simply a lateral displacement without any change of direction of the ray.

If one looks through a piece of clear, colorless glass, it is quite possible that he will be unconscious of the existence of the glass so long as his view does not include the edges. But the edges themselves stand out in marked contrast to the surrounding air. Assume, for the sake of simplicity, that a bundle of parallel rays are striking the glass at an angle less than the critical angle. Part of the light is reflected back from the surface of the glass and never reaches the observer. But the greater part passes through the glass to the observer without any change of direction. At the edges, however, some of the light is totally reflected back into the glass, some is totally reflected back into the air, some is refracted at varying angles from the glass to the air, and some is refracted at various angles from the air to the glass. Away from the edges, the light suffers no change readily perceptible to the observer. At the edges, it is broken up in a complicated heterogeneous fashion quite perceptible to the observer. Thus, the edges stand out in sharp relief both as compared with the glass and as compared with the surrounding air. But suppose the glass had the same refractive index, the same optical density, as the air. There would be neither reflection nor refraction at the edges, and therefore the edges would be invisible. That is, if the glass and the air were of the same degree of transparency and colorlessness, the glass would not be visible at all. This fact is utilized under the microscope to determine the refractive index of substances. This is discussed on page 33.

POLARIZED LIGHT

As previously mentioned, the phenomena of light are explained by means of the theory that light is simply a series of waves propagated in the ether. An ordinary candle flame owes its luminosity to the myriads of incandescent carbon particles it contains. Each of these particles sends out its own series of waves in all directions. Some of the waves impinge on and are reflected or refracted by various objects in various directions. Thus each reflecting or refracting object becomes a new source of light waves which may be again and again reflected or refracted by other objects, and so on, ad infinitum. In the heterogeneous complex of waves thus formed, certain waves may combine and increase their intensity, and certain other waves may neutralize each other. It is obvious that no satisfactory study of the effect of any ray of light on any particular object can be made under such conditions. An analogy with water waves may serve to make this clear. Think of a very large pond with the surface perfectly smooth. If a marble is dropped into the water a series of waves will spread out, circular fashion, from the place where the marble struck the water. This series of waves has certain definite properties which could be studied by their effects on various objects floating on the water. But suppose that, instead of one marble being dropped, a very large number had been simultaneously dropped. A series of waves would originate and spread out from each point where a marble had struck. But, before any particular wave had proceeded very far, it would meet other waves and become modified or even be destroyed. Objects floating on the water would show the effect, not of any particular series of waves, but of the chance combination of many series of waves, and consequently no study could be made which would directly show the relationship between the objects and a particular series of waves. Going back to the 1-marble series, it is obvious that at some point sufficiently distant from the point of origin the circumference of the circle formed by the waves would become so great that any short arc would be sensibly a straight line, a fact which would further simplify our study. Here the waves could be considered as simply a series of rises and falls of the water surface in one plane, whereas the waves arising from the many marbles would be rises and falls of the water surfaces in many planes at chance angles to each other.

Ordinary light is analogous to the many-marble case. Parallel-plane polarized light is analogous to the 1-marble case. Hence, parallel-plane polarized light can be defined as light whose wave vibrations are all in one plane.

Ordinary light can be polarized in several different ways. Perhaps one of the most universal methods is that of polarization by reflection. Light reflected from almost all polished nonmetallic surfaces is somewhat polarized. But there is a particular angle of incidence for each substance at which the reflected light is more completely polarized than it is at any other angle. This particular angle of maximum polarization is called the polarizing angle. In general it may be said that the polarizing angle is that angle of incidence at which the reflected and the refracted rays are at right angles to each other.

Polarization by reflection, however, is unsatisfactory, because of its incompleteness. The method usually employed in optical crystallography is polarization by a calcite prism, usually known as a Nicol prism. This brings us to the subject of double refraction, or birefringence.

DOUBLE REFRACTION

If a cleavage piece of clear calcite is placed upon a dot on a piece of paper, two dots will in general be seen on looking at the original dot through the calcite. If the calcite is placed upon a very narrow line on the paper, two lines will be seen at certain positions of the calcite. In other words, if a single beam of light is sent through a piece of calcite, two beams will emerge on the other side. Thus calcite has the power to split a beam of light into two beams. This property is possessed to greater or less extent by all crystalline substances which belong to some crystal system other than the isometric. In certain substances it is barely detectable even with the best instrumental equipment, and in other substances, such as calcite, it is easily detectable by the simplest method of observation. Between these two extremes are all gradations. As previously stated, a cleavage piece of calcite possesses the property of splitting a beam of light into two component beams. Each of these beams is plane polarized, and the plane of each is at right angles to that of the other. Consequently, when the beams emerge from the calcite we have plane-polarized light, but we have it polarized in two planes. By suitably cutting the crystal and recementing it, we can get rid of one of the rays by total internal reflection. Thus only one beam emerges and gives us plane-polarized light vibrating in one plane only. A piece of calcite thus cut is usually spoken of as a Nicol prism, or simply as a Nicol.

If two Nicols are so arranged that the polarized beam of light emerging from one, called the polarizer, enters the second, called the analyzer, the resultant phenomena depend on the angular relationship between the polarization planes of the two Nicols.

If the polarization planes of the two Nicols are parallel, the polarized beam passes through the analyzer without double refraction and emerges without any appreciable loss of brightness and without any change in the position of the plane of polarization. If, however, the analyzer be rotated, double refraction takes place, and one of the beams is lost by total reflection in the analyzer. The light, therefore, emerges from the analyzer with decreased brilliance. As the rotation of the analyzer is carried farther and farther, the light lost by internal total reflection becomes greater and greater, and consequently the light emerging becomes less and less. When the two Nicols are at an angle of 45° to each other, the lost light and the emerging light are about equal. When the two Nicols are at an angle of 90° to each other, all the light is lost, and none emerges. There are thus three relative positions of the two Nicols, which have considerable importance in optical crystallography: The parallel position, in which practically all the light emerging from the polarizer is transmitted through the analyzer, the 45° position, in which approximately half the light emerging from the polarizer is transmitted through the analyzer, and the 90° position, usually spoken of as the crossed

position, in which none of the light emerging from the polarizer is transmitted through the analyzer.

It happens that calcite has a very large double refraction. But all crystalline substances, other than those belonging to the isometric system, show double refraction to some extent, usually less than that of calcite.

Suppose a crystal of an isometric substance be placed between two crossed Nicols. Since the crystal has no double refraction, the light emerging from the polarizer is not altered and therefore enters the analyzer just as it would if the crystal were not present. No matter how the crystal is orientated, the effect, or rather, lack of effect on the light is the same. All of it is totally reflected internally by the analyzer, and the observer sees no light at all emerging from the analyzer.

But suppose a doubly refracting crystal be placed between the crossed Nicols. This crystal acts on the light emerging from the polarizer just as the analyzer would. If the plane of vibration of the polarizer and the crystal are parallel, the light emerges from the crystal with practically no diminution in brightness and with its plane of polarization the same as if the crystal were not present. This light is then lost in the analyzer by total internal reflection, again as if the crystal were not present, and the observer sees no light emerging from the analyzer.

If the crystal is rotated somewhat out of its position of parallelism, the light beam coming from the polarizer is doubly refracted anew into two beams with planes of polarization at right angles to each other. There is no arrangement in the crystal to absorb either of these beams as there is in the Nicols. Consequently both beams enter the analyzer. That small part of the light which is vibrating parallel to the plane of the analyzer is transmitted, and the observer sees the crystal faintly. As the crystal is rotated more and more, more and more light is transmitted until the 45° position is reached. At this position the crystal is the brightest. As the rotation becomes greater and greater, less and less light is transmitted, and the crystal appears less and less bright until the 90° position is reached, in which no light is transmitted and the effect to the observer is the same as at the beginning of the rotation.

On the basis of the phenomena shown by crystals when rotated between crossed Nicols, there are two great classes of substances, the singly refracting and the doubly refracting, or, in terms of their effects, those which remain dark during rotation and those which alternately light up and grow dark during rotation. This test is fundamentally one of the most important in optical crystallography. Not only does it give a ready method for distinguishing two major groups of crystals, but it has a very definite bearing on the refractive indices of a given crystal, as will be seen from the following.

It is a well-known fact that a ray of light, passing from a medium of one optical density into a medium of different optical density, is refracted or bent to a definite extent, depending on the difference in the densities of the two media. Suppose, however, that the second medium has different optical densities in different directions. Suppose simply that in certain directions the molecules of the medium are

more closely packed than they are in other directions. In short, suppose the space lattice of the second medium to be parallelopipeds. Then, for the same angle of incidence, the angle of refraction will be different, depending on the direction in which the ray of light enters the second medium. Consequently, the ratio of the angle of incidence to the angle of refraction will be different for different directions in the second medium. Assuming that the first medium is air, the refractive index of the second medium will then depend on the direction in this medium in which the light travels.

The parallelepipedon space lattice gives a crystal in which the packing of molecules is a maximum in a direction corresponding to one dimension of the parallelepipedons, a minimum in a direction corresponding to a second dimension, and intermediate between the other two is a direction corresponding to the third dimension of the parallelepipedons. The packing in any direction other than those corresponding to the three dimensions would then vary, depending on the relation between the direction chosen and the directions of the three dimensions. Correspondingly there would be three definite refractive indices, a maximum, a minimum, and an intermediate. Between the directions corresponding to these three indices there would be a series of varying indices, depending on the direction. All crystals belonging to the orthorhombic, monoclinic, and triclinic systems have these three major refractive indices.

Instead of the packing of molecules being dissimilar in three directions, suppose that in two of these directions the packing becomes the same; say that the packing in the minimum and the intermediate directions becomes identical. Then there are only two directions in the crystals in which the packing differs, a direction of maximum packing and a direction of minimum packing. Between these directions there would then be a series of directions in which the packing varied from the maximum to the minimum. Correspondingly, there would be two major refractive indices, a maximum and a minimum, with a series of varying indices depending on the direction of the light ray in the crystals. Substances belonging to the tetragonal and hexagonal systems have these two major indices.

If the molecular packing is further simplified so that the two directions of the previous paragraph become identical, so that every direction in the crystal has the same packing, there would be only one refractive index for the substance, and this index would be the same regardless of what direction in the crystal the ray of light took. Substances belonging to the isometric (cubic) system have simply one refractive index.

Summing up in reverse order: Isometric crystals have one and only one refractive index, usually denoted by n. Tetragonal and hexagonal substances have two refractive indices each, usually denoted by ϵ and ω. Orthorhombic, monoclinic, and triclinic substances have three refractive indices usually denoted by α, β, and γ.

For the complete study of the refractive indices of any given crystalline substance, one and only one index would have to be determined if the substance is isometric, two indices if the substance is tetragonal or hexagonal, and three indices if the substance is orthorhombic, monoclinic, or triclinic.

BECKE LINES

The critical angle may be further defined as that angle of incidence, of which the sine is equal to the reciprocal of the refractive index. If α denotes the critical angle and n the refractive index, thus,

$$\sin \alpha = \frac{1}{n}$$

Obviously, the greater is n the smaller will sin α be, and therefore the smaller will the angle α be. Suppose two substances of different refractive indices to be in contact along the line CC' (fig. 2) the normal to which is nn'. Let d' be the critical angle in the substance of higher index and b the critical angle in the substance of lower index. Then d' will be less than b. Then the angle c, the complement of d', will be greater than angle d, the complement of b. Suppose a ray of light be directed upward in the figure, with its center striking the contact of the two substances at C'. Then all the light within the angles c and d will be totally reflected and will emerge from the upper surface of the two substances, as shown in Figure 2. Since angle c is larger, it will contain a greater amount of light than d; and consequently a greater amount will be totally reflected and will emerge to the right of the contact than will be the case on the left of the contact. Light within the angle $b-a'$ will be partly reflected and partly refracted, and all light within the angles a' and d' will be partly reflected and partly refracted. But the sum total will be a preponderance of emerging light on the right side of the figure; that is, on the side of the substance of higher index. Therefore, the right side of contact will be brighter than the left side.

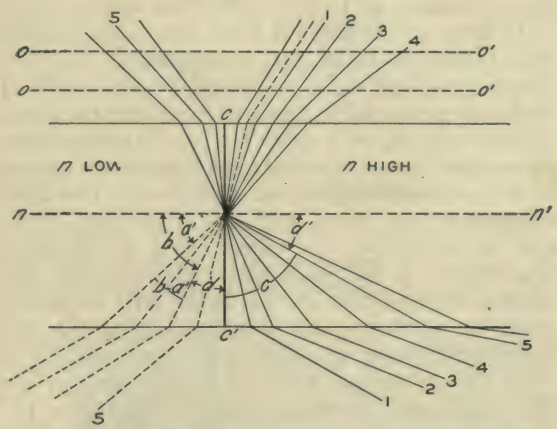


FIGURE 2.—Becke line production and movement

If a grain of high index is immersed in an oil of low index, the effect will be a line of light around the edges of the grain. If the plane of observation oo' is raised, it can be seen from the figure that the lines of light will apparently move farther to the right. If the plane is lowered, they will appear to move to the left. The effect on raising the plane is as if the area of the substance of higher index contracted, and on lowering the plane as if it expanded. The band of light is known as the Becke line, named after F. Becke by Salomon (*14*), and is one of the most commonly used phenomena in refractive-index determinations.

To make the phenomena concrete, suppose a grain of a substance, such as sodium chloride, having a higher index of refraction, be

mounted on a microscope slide in an oil of a lower index of refraction, such as cedar oil, and suppose the microscope be focused on the contact between the grain and the oil. A bright band of light will be seen to surround the grain. Now suppose the focal plane of the microscope be somewhat raised; that is, simply suppose that the tube of the microscope is slightly raised. The band of light will move into the grain. If the focal plane is lowered the band will move outward from the grain. If, on the contrary, the immersion oil had a higher index of refraction than the grain, as for example, cinnamon oil, the phenomena would be reversed. If the focal plane is raised the band of light moves outward from the grain into the oil, and if the focal plane is lowered the band moves inward toward the center of the grain. Put briefly, when the tube of the microscope is raised the band of light moves toward the substance of higher refractive index, and when the tube is lowered the band moves toward the substance of lower refractive index.

If both grain and oil have the same index of refraction, there will be no band of light and consequently no movement either way when the microscope tube is raised or lowered. If, furthermore, the oil and the grain have the same color and the same shade of color, or if both are equally colorless and transparent, the boundary line between the two is invisible, and one does not see the grain at all.

As has been explained previously, the refractive index of a given substance may vary with the direction of the light in the substance, but it is always the same in a given direction in the substance. Therefore, it happens that for a given grain in a given oil, the phenomena of the Becke lines will depend on the orientation, the position of the grain in reference to the incoming light. Methods for determining or altering this orientation will be given later.

If the substance belongs to the isometric system, the direction of the light, and therefore the orientation, is of no consequence. If the substance belongs to any of the other five systems, the direction of the light. and therefore the orientation. is of consequence.

INTERFERENCE OF LIGHT

If one drops a marble in otherwise perfectly still water and observes the effect of the waves thus formed on some small body floating on the water, it will be noticed that the body has simply an up-and-down motion, without any horizontal displacement. If the water moved horizontally, the body would move horizontally with it, and the fact that no such horizontal movement takes place is evidence that the wave motion itself is simply a progressive up-and-down movement of the surface of the water. At the spot where the marble strikes the surface there is at first a depression, and immediately afterwards there is a rise. This vertical movement, up and down, is transmitted to neighboring particles which consequently move up and down, and, in so doing, transmit the movement to still other particles. Thus, the up-and-down movement is propagated farther and farther from the source of the disturbance and is manifested as waves.

If (fig. 3) xx' is the level of an undisturbed surface, and *abcdefg* is the surface itself during wave motion, then the highest points of the waves, such as *b* and *f*, are called crests. The lowest points,

such as *d*, are called troughs. At the beginning of the wave, particles at the point *a* are just beginning to rise. Consecutive points continue to rise until the crest *b* is reached. But, although *a* and *c* are on the same level, the direction of movement at *a* is upward, whereas that at *c* is downward. The motion continues downward from *c* until the trough *d* is reached. Here the direction of motion is reversed, and a rise takes place up to the point *e*. Points *a* and *e* are both on the same level, and both have upward motions. From *e* the phenomena which started at *a* is repeated until the next similar point is reached, and so on. The distance *ae*, or the distance between any two points having the same level and corresponding directions of motion, is called a wave length.

As the motion of the wave progresses from left to right, any particle at a crest, such as *b*, will move vertically downward until it reaches a point *b'* the same distance below the level *xx'* as *b* is above it. Trough points such as *d* will move vertically upward to some point *d'*, making the distance $od' = od$. Intermediate points would have correspondingly intermediate motions; although it should not be forgotten that every point is, at some time, a crest, and at some other time a trough. The distance *ob*, that is, half the vertical distance from a crest to a trough, is called the amplitude of vibration.

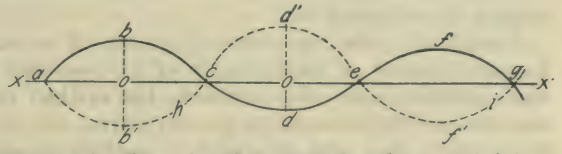


FIGURE 3.—Wave length, amplitude, phase, and interference of light waves

The wave length determines the color of the light. The longest waves which affect our eyes give us the sensation of red, the shortest violet. Other colors have intermediate wave lengths. Ordinary white light is a mixture of all wave lengths from that of violet to that of red.

The amplitude determines the intensity of the light. The intensity varies directly with the square of the amplitude. Any two points, such as *a* and *e*, *b* and *f*, or *h* and *i*, which are at a corresponding position relative to the plane *xx'* and have a corresponding direction of motion either up or down, are said to be in the same phase.

If two waves of the same wave length are superimposed so that every point in one is in the same phase as every corresponding point in the other, the wave length will remain unchanged. But the forces acting vertically on any point will be increased, and the amplitude of the new wave will be correspondingly increased. The intensity of the light will be increased.

If two waves of the same length are superimposed so that every point in one is in the phase opposite to that of the corresponding point in the other, the vertical forces will neutralize each other, and the amplitude of the new wave will be zero. In other words, there will be no wave at all, and darkness will be the result. Examples are extremely thin films such as soap bubbles when examined in monochromatic light. Here there will be observed a series of alternate bright and dark rings, the latter resulting from the interference of the light. If white light is used in place of monochromatic light,

only certain wave lengths interfere in given positions. These wave lengths are thus removed from the original white light and the residue of light reaching the eye is highly colored. The consequence is, therefore, that instead of dark rings, as with monochromatic light, there is a series of highly colored rings. The same phenomena take place when a cone of light is sent through a doubly refracting substance, as will be seen when interference figures are described (p. 39).

THE PETROGRAPHIC MICROSCOPE AND ACCESSORIES

MECHANICAL PARTS

The petrographic microscope and its optics have been repeatedly described, and adequate accounts of both the mechanical and optical features can be found in numerous texts of microscopy (7). The following description is therefore intended merely as a schematic representation, and for more detailed information the texts cited should be referred to.

Essentially the mechanical parts of a microscope are supports for, and means of adjustment of, the optical parts. They are therefore secondary in importance to the optical parts. Although of only secondary importance, poor supports can render a microscope inconvenient and illy adapted to certain purposes, and poor adjustments can actually make the instrument worthless in certain very necessary functions.

The base, which is usually of a modified horseshoe shape, should be large enough and heavy enough to prevent all tendencies of the microscope to topple when the upper part of the instrument is tilted a reasonable amount from the normal vertical position. On the other hand, it should not be so large as to be in the way of the manipulation or so heavy as to make the instrument unwieldy.

The pillar, in combination with the base should be high enough to allow adequate and convenient working space, between the stage and the base, for the substage equipment and the mirror. Short pillars are particularly annoying when, for example, the insertion of the finger between the substage and the mirror or the tilting of the mirror to obtain oblique illumination, is either impracticable or necessitates other operations.

The joint between the pillar and arm should allow easy tilting of the upper part of the instrument through an angle of 90° and should be provided with a clamp or other mechanism for maintaining any set inclination.

The arm is usually curved or is hollowed concave toward the stage in order to allow more working room on the stage. Other things being equal, that arm which is least in the way is perhaps best.

The fine-adjustment screw is the most important adjustment mechanism of the microscope and is perhaps the most apt to be faulty. This screw should have vernier attachments to allow the reading of complete turns and fractions of turns of the screw, and these readings should be directly convertible into vertical movements, expressed in decimals of millimeters, of the tube of the microscope. The pitch of the screw is not always the same in different parts, and for this reason it is essential that the mechanism be calibrated over

its whole length. This is especially true for instruments which have seen long service. The fine adjustment is not only a means of raising and lowering the tube in order to get a sharp focus on an object, but it is also a measuring device for the amount of raising or lowering. For these reasons the pitch of the screw should be as low and as uniform as practicable.

The coarse adjustment, usually a rack mechanism, should work smoothly and easily but should be tight enough to obviate all spontaneous movement of the tube.

The tube of the microscope usually consists of an inner drawtube and an outer body tube, the former fitting snugly into the latter and movable vertically in reference to the latter, preferably by an independent rack mechanism. The length of the body tube (the distance between the upper ends of the body tube and the shoulder of the objective screw) should be of known standard length, usually 160 mm. The drawtube should be conveniently ruled so that the increase in total tube length can be read when the drawtube is raised. In the tube there should be an iris diaphragm and slots or other arrangements for the reception of an auxiliary lens, a Nicol prism, a Bertrand lens, and other optical accessories. The base of the tube consists of a centering device and a clamp or nose piece for the attachment of the objective lenses.

The stage of the microscope must be of the horizontal revolving type, with the circle graduated in degrees and with appropriate verniers for reading fractions of degrees. While not absolutely necessary, two rectilinear movements of the stage governed by screws at right angles to each other are extremely useful and convenient. The stage should revolve easily and smoothly and should be preferably provided with a set screw for holding it in any given position. The usual clamps for slides must be provided on the table of the stage. These should be readily removable and replaceable. Universal stages, capable of revolving in every direction, are available in many forms and are frequently extremely convenient, especially in connection with the measurement of extinction angles (p. 58).

The substage mechanism must have a vertical movement, controlled by a rack, and also a swing-out movement. The rack should work smoothly and easily but should not be so loose as to slip spontaneously or under the influence of slight jars. The swing-out movement should be easily accomplished, without preliminary operations. Some means of readily removing and replacing the condenser lens, without disturbing the remainder of the substage, adds wonderfully to the satisfaction in using a good microscope. In addition to its optical equipment, the substage should carry an iris diaphragm and a swing-out frame for light filters and other accessories.

The mirror arm and fork must allow the rotation and turning of the mirror to any desired position without the removal of the substage or the lifting of the microscope from the worktable. The mirror fork should slide vertically and be clampable on the mirror arm.

Certain microscopes are equipped with a device for the simultaneous rotation of the two Nicol prisms, one in the tube and the other in the substage. This device consists essentially of two horizontal

arms attached one to each Nicol, the arms themselves being connected by an upright supported by the stage frame. The whole arrangement, including the Nicols, is capable of rotating horizontally through an angle of 90°, the angle being read by verniers attached to the device and moving on the graduated circle of the stage. Theoretically, it makes no difference whether the stage, and therefore objects under examination on it, revolves in reference to the Nicols or whether the Nicols revolve simultaneously in reference to the stage. In either case the final result is the same. There is also doubt as to which is relatively the easiest and more convenient. Some workers prefer the simultaneous rotation of the Nicols, whereas others dislike it. Perhaps, especially in much-used microscopes, the simultaneous rotation of the Nicols gives a steadier movement than would be given by a worn stage on a worn and clogged frame. On the other hand, the upright is occasionally very much in the way and must be detached. Since both can be had on the same microscope at the same time, the preference is to have both and to use either one or the other, depending on the exigencies of the moment or on personal inclination.

The foregoing brief description of the mechanical parts of a petrographic microscope emphasizes the fact that, up to a certain point, the parts are practically the same as those on any ordinary first-class compound microscope. Beyond this point, however, there are radical differences.

(1) The mechanical parts must carry much more optical equipment than the ordinary microscope. The latter usually has only the mirror, the condenser, the objective, and the ocular. The petrographic microscope must carry all of these, and, in addition, provision must be made for two Nicol prisms, auxiliary lenses, the Bertrand lens, quartz wedges, gypsum plates, quarter-undulation plates, and other accessories. (2) The mechanical equipment of the petrographic microscope consists partly of accurate measuring devices; for example, the fine adjustment screw and the graduated revolving stage, together with their verniers. The framework, therefore, becomes not only a carrier for the lens and lighting systems but also an accurately constructed measuring instrument as well. This point should be borne in mind when selecting an instrument for any other than a purely qualitative purpose.

OPTICAL SYSTEM

Although the mechanical equipment of the petrographic microscope has much more rigorous requirements than that of the ordinary microscope, the reverse is true so far as simple magnification is concerned. The prime and often the only requirement of the ordinary microscope is that it should magnify objects to clear visibility. This specialization of purpose has led to the development of lenses and illumination technic which give very great magnifications and very clear images.

As a rule, however, the petrographer and the optical crystallographer have very little interest in the appearance of the objects under examination. The interest is not in what the object looks like, but in the physical effect, frequently measurable, which the object has on light. In fact, the object is not at all visible during certain operations of optical crystallography, for example, the meas-

urement of axial angles. Furthermore, crystals are not generally so small as to require exceedingly high magnification. The result is that petrographic microscopes are not equipped for anything more than very moderate magnification but are equipped with a variety of physical appliances for the production of various optical phenomena which are not used at all in ordinary microscopy.

The mirror is so pivoted on the mirror fork and the mirror arm as to be rotatable any amount in any direction, thus enabling it to be set at any angle and thereby to perform its function of reflecting light from any source directly up into the microscope. One face of the mirror is plane and the other concave. The light reflected from the plane mirror into the microscope is parallel, and that from the concave mirror is convergent. The plane mirror, therefore, gives a weaker illumination than the concave mirror and is used with low-power lenses where a comparatively small amount of light is adequate. The concave mirror, on the other hand, is used with high-power lenses in order to increase the illumination by converging the rays of light. This rule, plane mirror for low magnifications and concave mirror for high magnifications, holds only when the condenser lens is not used. This subject will be discussed again in relation to condensers.

It should be noted here that parallel rays of light coming to the plane mirror from some very distant source, such as the sky, are reflected into the microscope with a slight loss of intensity. On the other hand, light from the same source is reflected into the microscope from the concave mirror with increased intensity, due to the convergence of the rays at the focal point of the mirror. If the light source is brought nearer so that the rays from it to the mirror are no longer parallel, the position of the focal point will change. Adjustment can be made to suit the conditions by sliding the mirror fork up or down the mirror arm, thus changing the distance of the mirror from the object under examination. In general, the nearer the source of light the greater is the focal distance of the mirror.

The condensing lens, as its name implies, is a lens for condensing and thereby increasing the intensity of the light which passes through it. Parallel rays of light passing into the lower surface of the lens are converged on passing out of the upper surface and thus form a cone-shaped bundle of rays meeting at the focal point of the lens. The light is therefore concentrated and the illumination consequently increased. If the light passing into the lower surface is already convergent, as is the case when the concave mirror is used, the convergency of the light leaving the upper surface of the condenser is increased and the focus of the condenser lowered. This lowering may very well bring the focus considerably below the object under examination and lessen, instead of increase, the illumination. For this reason it is generally best to use the plane mirror instead of the concave mirror, in conjunction with the condenser lens.

It is obvious that the best illumination will be obtained when the condenser lens is in focus. To bring it to focus any suitable object is mounted on the stage as usual and focused on with a low-power objective. The image of some fairly distant object, such as the edges of the window, is then projected into the field of the microscope by tilting the plane mirror. The condenser lens is now moved up or

down until the image is quite sharp. The condenser is now in focus. The image can be removed from the field by a slight tilting of the mirror. If the distance of the object from the condenser is changed it is evident that the condenser may need refocusing. Ordinarily this does not occur frequently, but it may occur if microscope slides of greatly different thicknesses are used.

The objective of the microscope is the lens, or usually the system of lenses, which is either screwed into or clamped onto the lower end of the microscope tube directly above the object under examination. It is perhaps the most important single item of the entire microscope equipment, since on it depends not only the magnification but also the clarity and sharpness of the image and consequently of all the other optical phenomena.

Objectives are usually corrected to some extent for spherical and chromatic aberration. Achromatic objectives are corrected for aberration of one color and for primary spherical aberration. Semi-apochromatic objectives are spherically corrected for two and apochromats corrected for three colors.

Oil-immersion objectives are those which are used in contact with a drop of oil, usually cedar oil, placed on the cover glass of the mount. Certain objectives require also a film of oil between the condenser lens and the slide. If the glass of the condenser lens, that of the slide, the cover glass, the objective lens, the immersion oil, and the mounting medium all have the same refractive index, there is a minimum loss of light since there is no refraction of the light when passing from one part of the system to another. Such a system is called homogeneous immersion. The nearer the respective refractive indices are together the less the loss of light. Water in place of cedar oil, for example, would lead to some light loss, and air in place of the water would lead to a still greater loss. It is obvious that only objectives of very short focus can be brought into contact with a drop of oil on a cover glass. Immersion objectives are therefore of high power. Loss of light with low-power objectives is of no practical importance. Dry objectives are those which have only air between the objective and the cover glass. The construction of dry and immersion lenses is different, and there is therefore no advantage gained by using immersion oils with dry objectives. In petrographic work, immersion objectives are practically never used.

Objectives are further described as having such and such angular apertures and numerical apertures, the latter usually being abbreviated to N. A. The angular aperture is the angle whose vertex is the focal point of the objective and whose sides are the light rays coming from the extreme edges of the lens. The greater this angular aperture is the greater will be the amount of light entering the objective from any point of the object and the better will be illumination. If the objective lens is immersed in some oil of a different refractive index, the focal point will change its position and consequently the angular aperture will have a new value. The axis of the lens always passes through the focal point and therefore always bisects the aperture angle, regardless of the position of the focal point.

Let i be the angle formed by the lens axis and the extreme rays passing into the objective, that is, let i be half the angular aperture

when the objective is immersed in air, and let r be the corresponding angle when the objective is immersed in some oil. Let n be the ratio of the sines of these two angles. Then,

$$n=\frac{\sin i}{\sin r},$$

or,

$$\sin i=n \sin r.$$

Instead of leaving the equation thus expressed in terms of the angle between the lens axis and the extreme rays entering the objective, we can let $2u$=angular aperture $=2r$.

Wherefore $r=u$.

Substituting, $\sin i=n \sin u$.

Defining $\sin i$ as the numerical aperture of the objective,

$$\text{N. A.}=n \sin u,$$

where n is the refractive index of the medium in which the objective is immersed. If the objective is of the dry type, $n=1$, and the formula becomes

$$\text{N. A.}=\sin u.$$

For dry objectives, therefore, the numerical aperture varies directly as the sine of half the angular aperture. For immersion objectives, the numerical aperture varies directly as the product of the refractive index of the immersion oil and the sine of half the angular aperture in that oil. The numerical aperture thus increases with the angular aperture. The greater the numerical aperture, the greater will be the amount of light entering the objective and therefore, in general, the better will be the illumination. Most manufacturers designate their objectives by numerical aperture, and it is consequently of importance to have some understanding of the meaning of the term.

The penetration or depth of focus of an objective may be defined as the vertical distance through which the image of an object may be seen sharply when the objective is focused in one position. With low-power objectives, both the bottom and top of fairly large objects may be seen sharply without any change of focus, but with high-power objectives this vertical range of distinct vision becomes considerably less, so that a change of focus becomes necessary in order to see objects in slightly different planes. The depth of focus varies inversely as the numerical aperture. For ordinary observational work a great depth of focus is very desirable, but for measurements of thickness the objective of least depth of focus gives the most accurate results.

Objectives may or may not have flat fields, that is, all points in one horizontal plane may or may not appear equally distinct at the same focus. Frequently, when the objective is focused on a point in the center of the field, the edges of the field appear blurred and require a new focus. This is especially apt to be noticed with high-power objectives and is due to the curvature of the image. Objectives showing this blurring within reason should not be considered as defective, since it is practically impossible to correct entirely for it.

The illuminating power of objectives, all other things being equal, varies as the square of the numerical aperture.

The resolving power of an objective is its capacity to render distinctly and separately visible two points which might otherwise appear as one. In other words, it is the capacity to render visible the finer details of objects. It depends on the correction for chromatic and spherical aberration and on the numerical aperture. Usually, the higher the magnifying power of an objective the greater is the resolving power, but this is not necessarily so. Examination of certain diatoms for finer details of structure is perhaps as good a test of resolving power as any.

The magnifying power of an objective depends on the tube length of the microscope. The greater the tube length the greater the magnification. Actual measurement of the magnification by the objective alone has practically no value, since the objective is always used in conjunction with some ocular. Magnification by a microscope, therefore, means the magnification produced by the objective and the ocular conjointly for a given tube length. Other things being equal, however, the magnification of a microscope depends directly and primarily on the magnification of the objective. Some objectives have their magnification marked directly on them; others are labeled variously.

In general, it may be said that objectives of low magnifying power are short and have a wide expanse of lense surface at their lower extremity. On the other hand, objectives of high magnifying power are long and have very little lens surface at their lower extremity. Objectives of intermediate magnifying power have intermediate appearances. The general subject of magnification will again be discussed in connection with oculars and methods.

The working distance of an objective is the distance of an uncovered object in focus from the front lens. Cover glasses and the brass mounting of the objective decrease this distance.

Dry high-power objectives are corrected for use with cover glasses of certain thicknesses, and a variation of 0.05 mm in this thickness may lower the efficiency of the objective. Usually the correction is for cover glasses from 0.16 to 0.18 mm thick. Water-immersion high-power objectives allow greater variation of cover-glass thickness than do the dry objectives. Low-power and homogeneous-immersion high-power objectives allow any reasonable variation in cover-glass thicknesses.

The ocular, which fits into the upper end of the tube and from which the light directly enters the eye, has for its function the magnification of the image formed by the objective. It is comparatively simple in construction, only two lenses being used in most forms. There are three general types, the Huygens, or negative ocular, the Ramsden, or positive ocular, and compensating oculars. The term "eyepiece" is frequently used as a synonym for ocular. In the Huygens ocular there are two plano-convex lenses with their plane surfaces upward, or toward the eye. The Ramsden ocular likewise consists of two plano-convex lenses, but the convex sides are placed toward each other. Compensating oculars are constructed to partly eliminate differences in focal planes for different colors caused by the objectives.

In addition to these general types, there are various special oculars which are more or less useful for various purposes. For ex-

ample, there are demonstration oculars, carrying pointers for indicating any part of the field; double-demonstration oculars, which enable two persons to view the same field at the same time; and goniometer eyepieces, which revolve horizontally on a graduated circle. A particularly useful form of ocular is one carrying a slot through which various accessories, such as micrometers, may be inserted. Oculars fitted with special optical equipment for the production of particular optical phenomena, such as the Bertrand ocular, will be described in connection with the phenomena.

Up to the present point the description of the optical parts of the microscope has been in general applicable both to the ordinary and to the petrographic microscope. Those appliances peculiarly characteristic of the petrographic microscope will now be described. Perhaps the most fundamental difference between the two types of instrument lies in the fact that the ordinary microscope uses ordinary light, whereas the light used in a petrographic microscope is plane polarized. The polarizer is located in the substage of the microscope and consists of a calcite prism cut and then recemented in a particular way. There are numerous types of Nicols, depending on their method of construction, but all accomplish the same purpose in the same general way.

If the calcite is cut and then recemented at such an angle that one of the rays strikes the planes of division at the critical angle or greater, whereas the other ray strikes the plane at less than the critical angle, the first ray will be totally reflected out of the side of the calcite and can be absorbed. The second ray, polarized in one plane, will pass through the calcite and can be used as a source of illumination for the microscope. The polarizer, therefore, causes a loss of about half the light coming from the mirror. This loss, however, is not serious as very high powers of magnification are not used.

In the tube of the microscope, above the objective, is another Nicol prism so arranged as to slide into and out of the path of light. This Nicol is also capable of rotation through an angle of 90° in order to enable the worker to set it so that its plane of vibration is either parallel to or at right angles to the plane of vibration of the polarizer. This upper Nicol is usually spoken of as the analyzer, and the analyzer and polarizer are said to be parallel or crossed, according to whether their planes of vibration are parallel or at right angles to each other.

Analyzers should not have sloping ends, as they not only cause a slight additional loss of light by reflection (which is not so serious) but displace the image of the object (which is very serious). All analyzers should be tested as to this latter point. Simply observe the positions of a number of small objects on a slide with the analyzer out and then reobserve their positions when the analyzer is inserted. The positions should not have changed to any very noticeable extent.

Certain types of microscopes, notably the "chemical" microscopes, place the analyzer, the so-called cap Nicol, over the ocular instead of in the tube, as is done in the petrographic microscope. This cap Nicol has its uses even in the petrographic microscope, and in the nonpetrographic type of instrument serves its purpose

very well. But for purely petrographic work the petrographic microscope with an analyzer in the tube will prove best.

Both Nicols should be quickly and conveniently removable for cleaning. The upper surfaces, especially of the analyzer, have a tendency to collect dust which interferes with clear vision. If the Nicols are not conveniently removable, cleaning is usually put off far beyond the time when the need arises. In the choice of instruments, the writer would consider the ease with which the Nicols could be cleaned as one of the crucial points affecting his decision.

The Bertrand lens, quartz wedge, gypsum plate, quarter-undulation plate, and micrometers are accessories to, rather than parts of, the petrographic microscope, but they are essential accessories and when used form an integral part of the optical system. Without them certain essential functions of the petrographic microscope could not be accomplished. They are, therefore, described in connection with the microscope, whereas other valuable but not indispensable accessories are described in connection with the particular optical phenomenon they are designed to produce or observe.

The Bertrand lens is inserted in a slot in the tube of the microscope and, together with the ocular, serves as a microscope for the magnification of the interference figure. The axis of the microscope and the center of the inserted lens should exactly coincide or should be easily adjustable to coincidence. This can be tested by observing the interference figure of a section of calcite cut at right angles to the optic axis. The center of the interference cross should lie at the intersection of the cross hairs of the ocular when the Bertrand lens is in place.

The quartz wedge, as its name implies, is, in its simplest form, a wedge-shaped piece of quartz mounted for protection between two plates of glass. This wedge is inserted into the tube of the microscope through a slot provided for the purpose. The increasing thickness of the wedge through which the light must pass, as the wedge is gradually inserted thin end foremost, causes increasing retardation of the light rays. Newton's whole range of colors is given, the colors repeating themselves in successive order as the wedge is inserted. One quartz wedge giving colors of the first, second, and third orders is essential, and another wedge giving colors of the third and higher orders is very desirable. There are various improved forms of quartz wedges which are really improvements; for example, the Wright combination wedge. But for ordinary petrographic work the ordinary wedge is usually sufficient.

The gypsum plate is variously spoken of as the selenite plate, violet of the first-order plate, red of the first-order plate, sensitive plate, and unit-retardation plate. It is insertable in the same slot as the quartz wedge and should have the same elongation as the wedge in order to avoid confusion. A method for testing this elongation will be given under the quarter-undulation plate.

The quarter-undulation mica plate is a sheet of muscovite of such thickness as to give a retardation of one-fourth λ, mounted for protection between glass plates. The quartz wedge, the gypsum plate, and the quarter-undulation plate have various uses which will be given in their places.

The vibration directions in the quarter-undulation plate can be ascertained or confirmed by using the plate as an object and observing the interference figure. The direction of least ease of vibration Z (or) is that of the line joining the foci of the two hyperbolæ. The direction of intermediate ease of vibration Y (or b) is at right angles to Z. To ascertain the vibration directions of the gypsum plate, use the plate as an object and observe the interference figure. The direction of the line joining the two yellow quadrants is the Z (or c) direction. The vibration directions of the quartz wedge can be ascertained by using the wedge as an object and inserting a quarter-undulation plate whose directions are known. This will be explained more fully under the use of the quarter-undulation plate.

At least two micrometers are absolutely essential. One of these should be a standard-stage micrometer with a scale marked off in tenths and hundredths of a millimeter. This micrometer should be used solely for calibrating other micrometers. The other essential micrometer is an eyepiece micrometer and may be of various types. Certain types are circular in shape and are inserted into the ocular. Other and more convenient types are mounted on a rectangular frame which slides into a slot provided for the purpose in the ocular. If only one eyepiece micrometer is to be had, the checkerwork type is the more useful. It is best, however, to have one of this and also one of the linear-scale type. Various screw-micrometer oculars for great refinement of measurement can be had and should be used when extremely accurate results are necessary. For ordinary petrographic purposes the standard-stage micrometer and a suitable checkerwork eyepiece micrometer will be adequate.

Where reflected light is to be used, the vertical illuminator will be found invaluable. It is a device attachable to the lower end of the microscope tube between the tube and the objective. A horizontal beam of light is admitted through an iris diaphragm in the side of the illuminator, is then reflected vertically downward by a semicircular rotatable mirror, passes through the objective onto the object, and thence is reflected back vertically upward through the objective and illuminator to the eye.

CALIBRATION AND MEASUREMENTS

TO DETERMINE THE VIBRATION DIRECTIONS IN NICOL PRISMS

Prepare a section of biotite cut at right angles to its cleavage. Rotate this section, with analyzer out, until it is in its darkest position. The cleavage direction is now parallel to the plane of vibration of the polarizer. If a suitable section of biotite is not available, mount a minute crystal of tourmaline, in which the elongation (the direction of the c axis) can be identified, so that the c axis is horizontal. Rotate the mount, with analyzer out, until the crystal is in its darkest position. The c axis will now be at right angles to the plane of vibration of the polarizer. Another less accurate, but nevertheless fairly satisfactory, method is to detach the polarizer from the microscope, reflect light into the polarizer by means of a preferably horizontal piece of plate glass or other polished surface,

and rotate the polarizer until the glass appears dark. The vibration plane of the Nicol will now be at right angles to the reflecting surface.

The vibration plane of the analyzer can be readily found by comparison with the polarizer. Set the polarizer in some definite position in the microscope and use a good light. Rotate the analyzer until the field is dark. The Nicols are now crossed; that is, their vibration planes are at right angles to each other. The position of the vibration plane of the polarizer being known, that of the analyzer is known also.

The Nicols should be so placed in the microscope that the cross hairs of the ocular are parallel to the vibration planes when the Nicols are crossed.

DETERMINATION OF THE MAGNIFYING POWER OF A LENS SYSTEM

The magnifying power of a lens or system of lenses is not the definite figure it is usually thought to be. The magnification is the number of times the diameter of the object is contained in the diameter of the image; that is, it is the ratio of the diameter of the image to the diameter of the object. But the diameter of the image varies with its distance from the eye, and different eyes see most distinctly at different distances. The magnification is thus a constant, the diameter of the object, divided into a variable, the diameter of the image, this latter being large for far-sighted eyes, smaller for normal eyes, and still smaller for short-sighted eyes. The distance of most distinct vision for normal eyes is somewhere about 10 inches (250 mm). This is usually taken as a standard. It can be shown by elementary geometry that the ratio of the diameter of the image to the diameter of the object is approximately the same as the ratio of the distance of distinct vision to the focal length of the lens. Taking 250 mm as standard, the magnification, N, is then

$$N=\frac{250}{F},$$

where F is the focal length. This is simply a convention and different observers would actually see very differently. For example, a lens of 25 mm focal length would show an apparent magnification of ten times to a normal eye and only five times to an eye which saw most distinctly at a distance of 125 mm (5 inches).

The magnifying power of a microscope may be directly measured by placing a stage micrometer directly on the stage. The microscope is carefully focused on this micrometer. Any suitable scale, for example an ordinary desk rule, but preferably one with units directly convertible into the stage micrometer units, is then placed horizontally beside the microscope at a distance of 250 mm from the exit pupil of the eye. The image of the stage micrometer is observed with one eye and the scale with the other. The scale is moved about horizontally until it coincides with the image of the micrometer. Direct comparison of the two can now be made. If, for instance, the image of a $\frac{1}{10}$-mm division on the micrometer tallies end to end with a 10-mm division on the scale, the magnifying power of that particular lens combination is 100 diameters.

A better method, perhaps, is to use a camera lucida, if one is available. Place a piece of paper at such a distance from the eye that the actual path of the ray through all its reflections in the camera lucida from the paper to the eye is 250 mm. On the paper mark off the extremities of some convenient division, say a $\frac{1}{10}$-mm division, of the micrometer image, as seen on the paper through the camera lucida. Measure the distance between the two marks, and find the ratio between this measured diameter of image and the actual size of the micrometer division. If, for instance, the micrometer division is $\frac{1}{10}$-mm and the distance between the marks is 25 mm, the magnifying power is 250 diameters.

It is not often that one absolutely needs to know the magnifying power of a lens system except as it can be obtained comparatively by simple inspection of the objectives and oculars. It is essential, of course, to know that one objective or ocular will give a higher magnification than another. But to know that one lens combination gives a magnification of exactly 280 diameters, for instance, is usually information of doubtful utility.

HORIZONTAL LINEAR MEASUREMENTS UNDER THE MICROSCOPE

There are several methods for measuring lengths of microscopic objects. The simplest is to use a micrometer stage. This is an arrangement whereby two screws, with vernier attachments, working at right angles to each other, are capable of moving the stage and consequently any object on it. The screws should be calibrated by placing the stage micrometer on the micrometer stage (the distinction should be noted), aligning the screw axis with the stage micrometer and comparing the divisions of the screw vernier with the distances actually passed through by the stage as shown by the cross hairs and the stage micrometer. This calibration should extend through the entire lengths of both screw movements. To measure the length or diameter of any object under the microscope, align the screw axis and the linear direction desired, place one end or side on the cross hair, and turn the screw until the other end or side is on the cross hair. The length or diameter is then given directly by the screw divisions turned through.

A more generally satisfactory method involves the use of the eyepiece micrometer. This micrometer should be calibrated once for all by means of the stage micrometer and for every lens combination. This can be readily done by simple comparison of the images of the two micrometers as seen directly through the microscope. It would seem unnecessary to remark that this comparison does not give directly the magnifying power of the microscope, but experience shows that this is one of the commonest of mistakes. All that is actually done is to compare an image of the stage micrometer magnified by the entire lens combination with an image of the eyepiece micrometer magnified by one or more of the lenses of the ocular only. All that is directly known is that a unit division of the eyepiece micrometer corresponds to so many millimeters, as read on the stage micrometer, and this is all that one needs to know. If the stage micrometer is replaced by an object, the length can be read directly from the eyepiece micrometer. This length expressed as numbers of eyepiece-microme-

ter units multiplied by the value in millimeters of a unit gives the actual length of the object. The checkerwork or net-grating eyepiece micrometers are much more satisfactory than the linear-scale type, as lengths in two directions at right angles to each other can be read without moving the object and diagonal lengths can be immediately calculated by application of the theorem that the square on the hypotenuse is equal to the sum of the squares on the other two sides. Thus any horizontal dimension of an object can be directly read or calculated without altering the position of the object. The objection to the checkerwork micrometer is that the large number of lines engraved on it sometimes interfere with distinct vision. This is unquestionably a valid objection; but the inconvenience of removing and replacing the micrometer, especially if it is of the slide type, is almost inconsequential as compared to the ease and range of measurement available. Generally speaking, however, it is best to have both the linear and checkerwork types of micrometers and, of the latter, one with very small and another with comparatively large unit squares.

There are several types of screw-micrometer oculars available. In principle these are screw-vernier arrangements for moving the micrometer over the image of the object instead of vice versa, as with the micrometer stage. The screw micrometer is capable of giving results of a very high degree of accuracy.

MEASUREMENT OF THICKNESS

The most delicate method of measuring the thickness of a particle is by means of its double refraction. The procedure is exactly the reverse of that given for the determination of the double refraction (which see). This method of thickness measurement, however, is very limited in its application. (1) The substance whose thickness is desired must be doubly refracting, and this requirement eliminates the possibility of applying the method to isotropic substances, including cover glasses and other very common objects. (2) It is necessary to know not merely the maximum double refraction of the substance as listed in the books or as usually determined, but it is essential to know the double refraction of the substance in the particular orientation in which the thickness measurement is to be made. This kind of information is very seldom available. In the rare cases where it is available, however, the method is to be highly recommended both for its accuracy and speed. The procedure is as follows: Rotate the stage until the object is in a position of maximum brilliance between crossed Nicols. Insert the quartz wedge into the tube of the microscope. If the colors of the object mount in the color scale as the wedge is inserted, rotate the object an additional 90°. If they descend in the color scale leave the object as it is and continue the insertion of the wedge until the object, at the point where the thickness is to be measured, becomes black. By removing the object or observing vacant spots in the field of the microscope and counting the number of recurrences of the color as the wedge is withdrawn, the color and its order are identified. Find the double refraction along the upper or right margin of the Michel-Lévy chart. (Fig. 5.) From this point follow the diagonal line to the particular

color of the particular order identified with the wedge. Then follow the horizontal line to the left margin of the chart, where the thickness will be found.

A method of thickness measurement practically universal in its application consists, in principle, in focusing on the plane of the bottom of the object, then refocusing on the plane of the top of the object and reading the difference between the two focal positions, the rise of the tube of the microscope, from the fine-adjustment screw and vernier. This presupposes that the fine adjustment be accurately calibrated. Furthermore, the reading from the fine-adjustment screw will not be the same when the focusing is done through air, as when it is done through the object. There are therefore two cases under this method. The calibration of the fine-adjustment screw presents difficulties, especially to workers of limited experience and equipment, and neither the calibration nor a thickness measurement can be any more accurate than the worker's ability to bring the microscope to a sharp focus and to duplicate this focal reading after raising or lowering the tube of the microscope. It is perhaps true here, more so than in any other phase of microscopic work, that the eye of the observer is as much in need of checking as is the instrument. Fine-adjustment screws undoubtedly do come uncalibrated or occasionally badly calibrated, but it is manifestly unjust to condemn a screw on the basis of results obtained by a person physiologically incapable of obtaining reliable results. There is no desire on the writer's part to stress this point unduly, but it is just as well to face the fact that there are individuals just as much unfitted, physiologically and psychologically, for microscopy as there are other individuals unfitted for music or art.

A fair method of calibrating the fine-adjustment screw is by the use, as object, of a cover glass, the thickness of which has been determined by micrometer calipers. Turn the fine-adjustment screw down as far as practicable, focus on the plane of the lower surface as accurately as possible with the coarse adjustment, complete the focusing with the fine adjustment and read the vernier. Turn the fine adjustment until the focus is on the plane of the upper surface. Again read the vernier. The difference between these two readings divided into the thickness of the cover glass gives the average value for one division of the fine adjustment for the particular screw range used. Leaving the fine adjustment in its last position, lower the tube of the microscope by means of the coarse adjustment to as accurate a focus as possible on the lower plane of the object. Complete the focus with the fine adjustment. This will give a new point of departure which will probably overlap slightly with or leave a slight interval between it and the first range of reading. Raise the tube of the microscope by means of the fine adjustment to a focus on the upper plane of the object. The difference of the readings divided into the cover-glass thickness will give an average value for each division of the fine adjustment over this new screw range. Continue in this way until the upper limit of the screw is reached. Then begin again with the first focus of the fine adjustment adjusted at a different reading from that found at the beginning. This process of calibration can be carried to any desired degree of elaborateness.

If, after a number of complete traverses of the screw have been made, it is found that the averages are all approximately the same, the screw divisions can be considered as calibrated at this average value. If two of the averages are markedly different, the data of the readings will indicate approximately the position in the screw where the trouble is, and this position can be avoided when making future thickness measurements. This process of calibration can be immensely shortened by confining it to one or two complete turns of the screw near the center of the screw range; or, better still, by confining it to the small number of intervals plus a few both above and below the range actually involved in the measurement. This latter procedure has the advantage of providing a check on the screw every time a series of thickness measurements is made, an advantage which becomes more and more important as the microscope becomes older. In making thickness measurements, all focusing with the fine adjustment should be made by movements all in the same direction, either up or down, in order to avoid errors due to lost motion. It should be borne in mind that there are very few fine adjustments which give identical values for each interval over the entire screw length. A certain amount of tolerance is therefore necessary, and occasional rechecking is all the more desirable. An accurate calibration over a small number of uniform intervals is much more satisfactory than an average calibration of the entire screw.

If an object is lying on a microscope slide, the upper surface of the slide can be taken as the plane of the lower surface of the object. By focusing on a scratch or a dust speck on the slide, reading the fine adjustment, then raising the tube by means of the fine adjustment until the upper surface of the object is in focus and again reading the fine adjustment, the difference of the two readings gives a measure of the thickness of the object. But this measure will be different, depending on whether the focusing on the slide surface has been to one side of or through the object. If the point of focus on the slide and that on the upper surface of the object are very close together horizontally, and if the focusing has been done slightly to one side of, and not through, the object, the difference of the fine-adjustment readings, converted into its calibration units, gives directly the thickness of the object. The object of course can be placed at any desired spot on the slide preliminary to the focusing. If the object is flat and has edges sloping outwardly and down, the lower edge can be used as a point of focus instead of the scratch or dust speck.

At times it is necessary to do the focusing through the object. Proceed exactly as above and then multiply the value so obtained by the refractive index of the object. This gives the true thickness. A mounting medium acts in this respect just as does any other object, and therefore thicknesses measured by focusing through the mounting medium must be multiplied by the refractive index of the medium in order to obtain the true thickness. If the lower focus is determined through air, no such multiplication is necessary, since the refractive index of air is unity.

Measurements of slant distances can be made by combining the proper horizontal and vertical measurements. The slant distance

between any two points is the square root of the sum of the squares of the vertical and horizontal distances.

Very fair ideas of the shape of vertical sections of objects with curved surfaces can be obtained by plotting vertical distances as ordinates and horizontal distances as abscissæ and connecting the points by a smooth curve. This is not very often of use and is not very accurate when applied to extremely small objects. A far easier method is to roll the object over and observe its shape directly or with the aid of the eyepiece micrometer when quantitative results are desired. But cases may arise where the rolling is impracticable. The graph method may then serve a good purpose.

MEASUREMENT OF AREAS

Perhaps the most convenient and readily accessible method of measuring areas under the microscope is to use a closely lined checkerboard micrometer and to count the number of micrometer unit squares covering the image of the object. If the micrometer has been previously calibrated against a stage micrometer, as described above, the area of each unit square is known, and the area of the object is simply this unit area multiplied by the number of units. Since proportional areas rather than absolute areas are usually desired, it is perfectly permissible to state areas directly in terms of micrometer units, regardless of what the calibration of the micrometer may be. For very close work, parts of unit squares on edges of the object's image can be estimated and added to the total. Micrometers so lined as to be directly readable in blocks of units, twenty-fives, and hundreds greatly facilitate the count and relieve eyestrain. At the very best, a worker will occasionally lose sight of the place under count. This may necessitate doing all the counting again, with the possibility of again losing the place, unless some system is used. A fairly satisfactory system is to first count all complete blocks of hundreds, then all complete blocks of twenty-fives not included in the hundreds, then all units not included in either of the preceding, and finally all fractions of units on edges of the image. In case of losing place, it is then necessary to repeat the count only partly instead of completely.

Areal estimations can be made by photographing or drawing with a camera lucida through the microscope, cutting out the areas desired and weighing them, the areal proportion being the same as the weight proportion on the assumption that the paper is perfectly uniform. The paper can be backed with tin foil to give added weight and therefore more accurate results. This method can be used in the absence of a micrometer but is otherwise not recommended.

A statistical method consists in making a number of linear measurements at right angles to each other for numerous particles in a given mount. These measurements, added and averaged, give a rectangle, the area of which can be compared with that of another rectangle similarly obtained. Better results have been obtained with this method and its modifications than would normally be expected; but, owing to the large number of measurements necessary, the method is tedious and long.

MEASUREMENT OF ANGLES

As a preliminary to the measurement of an angle, the stage of the microscope should be very carefully centered. The slide should then be moved until the vertex of the angle is at the intersection of the cross hairs and one side is very near and parallel to one or the other of the cross hairs. A reading is taken from the graduations on the circumference of the stage. The stage is then rotated until the second side of the angle reaches the initial position of the first side. A second reading is taken, and the difference between it and the first reading gives directly the angle desired. Instead of "sides" to the angle one may have cleavage directions or directions of extinction, but the technic is the same. These angular measurements should be repeated, using first one side then the other as the initial side and revolving the stage in opposite directions. Then the stage should be turned 180° from its first position and the measurements repeated in this new position.

A goniometer eyepiece may be used in place of the rotating stage. The only essential difference between the two methods is that with the goniometer eyepiece the object stays still and the cross hairs rotate, whereas with the revolving stage the object rotates and the cross hairs remain still.

Angles can be measured from camera-lucida drawings or from photomicrographs by means of an ordinary protractor. An approximation to an angle can be obtained by use of the checkerwork-eyepiece micrometer and a table of trigonometric functions.

If the angle between two crystal faces is being measured, the methods above give the true angle only when the planes of the faces are parallel to the axis of the microscope, or (which is practically the same) when the intersection of the two faces is vertical. Preliminary examination as to these points should be made before the angle is measured. It should be remembered also that the angle measured is the actual angle between the two faces and not its supplement as read from a reflecting goniometer. Angles between horizontal and vertically slanting faces can sometimes be calculated from data derived from horizontal measurements with the eyepiece micrometer, together with vertical measurements with the fine adjustment. There are various other angles which may be calculated by methods of plane and solid trigonometry, but the need for them is comparatively rare, and reference is therefore made to the standard text (*2*). The beginner, when dealing with the angular measurements of crystals, should be particularly careful not to be misled by misshaped or unusually oriented crystals. A cube of common salt, for example, shows a beautiful hexagonal outline when it is tilted with a corner uppermost and is examined with an objective of considerable depth of focus. The measurements of these hexagonal angles would be utterly meaningless, and a very casual examination with a lens of less depth of focus would reveal the true form of the crystal. This serves to illustrate one of the essential tests which should never be omitted before making an angular measurement. Both sides of the angle should simultaneously come into focus over their entire length when examined with an objective of minimum depth of focus.

There are apparent exceptions to this rule, but it is safer to follow it than to read angles indiscriminately, at least until one acquires the habit of thinking crystallographically.

OPTICAL METHODS

IMMERSION MEDIA

In all microscopic work immersion media of one kind or another are used in making up the mounts for examination. Their purpose, primarily, is to aid visibility and, secondarily, in conjunction with the cover glass, to protect both the object and the objective lens. The preparation of the mount may become a very complicated matter or may be of the utmost simplicity, depending on the nature of the object and the purpose to be attained. Essentially, however, it consists in embedding an object on a slide in the immersion medium selected and then placing a cover glass over the object. The choice of the immersion medium is a matter of the utmost importance, especially in the determination of the refractive indices of objects. If we mount, say, a broken fragment of glass in some oil of a known refractive index different from that of the glass, the glass is easily visible. If by trial we mount the same glass in oils of refractive index progressively nearer and nearer that of the glass, the glass is invisible. Thus, knowing the refractive index of the oil in which the glass is invisible, we also know the refractive index of the glass.

Ideally, immersion media which are to be used for refractive-index determinations should have the same color and the same intensity of color as the substance to be examined. They should be stable in contact with air and under the influence of light; they should be practically nonvolatile in air, and especially they should not be differentially volatile; and their refractive indices should not vary perceptibly with ordinary changes of temperature. They should have no, or only slight, dispersive effects on light, they should not dissolve the substances to be examined, and they should all be mutually miscible so as to enable the worker to form media of refractive indices intermediate between any two given indices. Needless to say, no such ideal set of media has ever yet been contrived. There are, however, several practicable sets. Larsen (*10*) gives the refractive indices shown in Table 1.

TABLE 1.—*Refractive indices of immersion media*

	n at 20° C.	$\frac{dn}{dt}$	Dispersion	Remarks
Water	1.333	Slight.		Dissolves many of the minerals with low indices.
Acetone	1.357		Slight	
Ethyl alcohol	1.362	0.00040	do	Do.
Ethyl butyrate	1.381		do	
Methyl butyrate	1.386		do	
Ethyl valerate	1.393		do	
Amyl alcohol [1]	1.409	.00042	do	Dissolves many minerals with which it is used.

[1] Ordinary fusel oil may be used, but on mixing with kerosene it forms a milky emulsion, which settles on standing, and then the clear liquid may be decanted off.

TABLE 1.—*Refractive indices of immersion media*—Continued

	n at 20° C.	$\frac{dn}{dt}$	Dispersion	Remarks
Kerosene	1.448	.00035	Slight	
Petroleum oil [2]				
Russian aboline	1.470	.0004	do	
American aboline	1.477	.0004	do	
Valvolene [3]	1.502	.0004	do	Will not mix with clove oil.
Clove oil [4]	1.531	.00050	Moderate	Will mix with petroleum oil.
Cinnamon oil [5]	1.585 to 1.600	.0003	Strong	
Cinnamon oil from Ceylon	1.595	.0003	do	
Cinnamic aldehyde	1.614 to 1.617	.0003	do	
α Monobromnaphthalene [6]	1.658	.00048	Moderate	
Methylene iodide	1.737 to 1.741	.00070	Rather strong	Rather expensive. Discolors on exposure to light, but a little copper or tin in the bottle will prevent this change.
Methylene iodide saturated with sulphur.	1.778		do	
Methylene iodide, sulphur and iodides.[7]	1.868		do	
Piperine and iodides	1.68 to 2.10			
Sulphur and selenium	1.998_{Na} to 2.716_{Li}		Very strong	
Selenium and arsenic selenide.	2.72 to 3.17_{Li}		do	

[2] Any of the medicinal oils may be used, such as Nujol.
[3] Any good, clean lubricating oil, such as is used in automobiles, may be used.
[4] If clove oil does not mix with petroleum oil mix it with rapeseed oil, $n=1.471$.
[5] The only advantage in using cinnamon oil is that it is less expensive than cinnamic aldehyde.
[6] Mixtures of clove oil and α monobromnaphthalene give a set of liquids of lower dispersion than those with cinnamon oil.
[7] To 100 g[8] methylene iodide add 35 g iodoform, 10 g sulphur, 31 g SnI_4, 16 g AsI_3, and 8 g SbI_3, warm to hasten solution, allow to stand, and filter off undissolved solids. See Merwin (*12*).
[8] g is the abbreviation for gram or grams recently adopted by the style manual for United States Government printing.

In making mixtures of two oils to obtain media of intermediate indices, the equation

$$v_1 = n_2 - n$$
$$v_2 = n - n_1$$

where v_1 is the volume of the oil of least index, v_2 the volume of the oil of greater index, n_2 the greater index, n the desired index, and n_1 the lesser index, will be found useful. The refractive index of the mixture prepared in the proportions given by the equation must, however, be measured, as the formula is only approximately correct. The measurement can be made on any refractometer having a sufficiently wide range of readings or can be made somewhat less accurately by a reversal of the process for measuring the refractive index of crystals (which see). Sets of calibrated liquids are on the market.

DETERMINATION OF REFRACTIVE INDEX BY BECKE LINE

Assuming that we are dealing with an isometric substance or with a crystalline nonisometric substance whose orientation can be modified or determined to suit our convenience, we have the following method for determining the refractive index by means of the Becke line.

Mount the substance in any immersion medium of known refractive index. Either the grain and the immersion medium have the same refractive indices or they have different refractive indices. If they have the same refractive indices, the substance will be invisible and will have the same index as that of the medium of

known index. The refractive index of the substance is therefore known.

Almost never, however, would one be able to guess so well or happen to pick the right medium the first time. Practically always the refractive indices of the medium and the substance would be different. In this case focus the microscope on an edge of a grain of the substance. Raise the microscope tube by means of the fine-adjustment screw. If, when the tube is raised, the Becke line moves into the grain, the grain has the higher index; if the Becke line moves outward from the grain, the immersion medium has the higher index. We have thus determined whether the given medium has a higher or lower index than the grain. If its index is lower than that of the grain, obviously we need a medium of higher index. If its index is higher, obviously we need a medium of lower index. Choose another immersion medium on the basis of what has been said in the previous sentence and make another mount. Repeat the observations on the Becke line. In the first mount we found, say, that the index of the grain was the higher:

$$n \text{ (first medium)} < n \text{ (grain)}$$

In the second mount we will find either that

$$n \text{ (first medium)} < n \text{ (second medium)} < n \text{ (grain)}$$

or

$$n \text{ (first medium)} < n \text{ (grain)} < n \text{ (second medium)}$$

In the first case we have found a medium which has a known index nearer that of the grain. That is, we are closer to the true index of the grain than we were in the first mount. In the second case we have established limits between which the index of the grain must lie. By repeating this trial and error method a sufficient number of times we will finally find a medium in which the grain is invisible. The refractive index of the grain is then the same as that of this medium, and since the index of the medium is known that of the grain is also known.

In the use of the Becke line for refractive-index determinations several precautions must be taken as follows:

(1) The grains of the substance to be examined must be dry before they are mounted in any immersion oil. Otherwise, the Becke line is the result, not of the contact between the oil and the grains, but of the contacts between the oil and water and of the water and the grains. The result usually is a heterogeneous mixture of Becke lines practically impossible of interpretation into terms of the refractive indices of the grains and the immersion medium.

(2) The substance under examination should be insoluble, or practically so, in the immersion media used. If the substance is appreciably soluble in the media, the Becke line is the result not of the contact of the substance and the media, but of the contact of the substance and a solution of the substance of unknown concentration and therefore of unknown refractive index.

(3) The surfaces and edges of the grains of the substance to be examined should be clean and free from coatings and adhesions of

foreign substances. If these coatings and adhesions are readily visible, their presence can be recognized and search made for edges which are free from these impurities. But grains coated with thin films of transparent impurities are likely to cause errors. Such coated grains are frequently encountered in substances which have been dried without first having had the coating of mother liquor removed. If such grains are crushed, edges free from the coatings can be readily found.

(4) The line of contact between the grain and the immersion oil should be as nearly vertical as possible. With a transparent thin grain, both the top and bottom edges are visible. If the side contact between the grain and the oil is very much inclined from the vertical, Becke lines may be seen to move both from the bottom and top edges, and confusion may result. Furthermore, the phenomena are complicated by reflection and refraction from the inclined surface.

(5) One should make sure that he is examining an individual crystal and not an aggregate of small crystals. In any given spot in an aggregate, the light effect would be the chance composite of the effects of all the small crystals through which the light had passed and would have no determinable relation to the effects of any given crystal. At different spots on the aggregate the light effects would vary, depending on the uniformity of sizes, orientation, distribution, and degree of packing of the smaller crystals. Especially should one look out for twinned crystals.

(6) One should make sure that he is examining crystals and not skeleton crystals, that is, crystals in an incipient stage of formation. Although the writer has no data on this subject, he is fairly sure that he has noticed several times that skeleton crystals had optical properties quite different from those of the completed crystal.

DETERMINATION OF TWO INDICES OF REFRACTION

The simplest procedure in determining both refractive indices, ω and ϵ, of a uniaxial substance is to find a crystal with a recognizable c axis in the horizontal position. Rotate to extinction between crossed Nicols, with the c axis parallel to the vertical cross hair. Remove the analyzer and by means of Becke line determine whether the crystal in this position has a higher or lower index than that of the embedding oil. Proceed then with the method already described for isotropic substances, except that here all the observations must be made on crystals in the initial orientation, or in that position of extinction which has the c axis parallel to the vertical cross hair. Finally, an oil will be found in which the crystal, in the given orientation, will be invisible. The refractive index of the oil being known, that of the crystal in the given position is also known. Repeat the whole procedure as above except that the crystal is to be in the position of extinction with the c axis at right angles to the vertical cross hair, that is, parallel to the horizontal cross hair. If the given substance is optically positive, the greater of the two indices measured as above is ϵ and the lesser one is ω. If the substance is optically negative, the greater is ω and the lesser ϵ.

If the refractive index is determined as above on grains, so orientated that the optic axis is vertical, that is on grains which give as

interference figure the uniaxial cross with the center in the center of the field, the index is ω.

If refractive indices are determined for two positions of extinction for a number of grains in random orientation, it will be found that one of the two values will be the same in all the grains. This constant index is ω. The other value will vary from grain to grain depending on the orientation. That value which is farthest from ω is nearest ϵ. Since uniaxial grains have a tendency to lie with the c axis horizontal, this value will perhaps be ϵ. Statistically the highest and lowest indices determined on a large number of grains of the same substance in random orientations will be the maximum and minimum indices of the substance and therefore will be ω and ϵ or ϵ and ω, depending on the optical character of the substance. But selection of grains in proper orientations when possible obviates the necessity for statistical methods.

All the foregoing may be summed up as follows: The refractive index of uniaxial crystals varies with the orientation of the crystal, but for a particular substance in a particular orientation, the index is constant. Therefore, to determine the refractive indices of a particular substance, proceed exactly as with isotropic crystals, except that orientation can not be disregarded as in the case of isotropic substances. Uniaxial substances with the optic axis vertical give ω no matter where the stage is rotated. Uniaxial substances with the optic axis horizontal give ω at one position of extinction and ϵ when rotated 90° to the next extinction. Uniaxial substances with the optic axis neither vertical nor horizontal give ω at one position of extinction and some value between ω and ϵ when rotated 90° to the next position of extinction. Every orientation therefore allows the measurement of ω, but only one orientation allows the measurement of ϵ. Crushed quartz, crystals of sodium nitrate, calcite, and apatite serve very well for demonstrations of the foregoing.

DETERMINATION OF THREE INDICES OF REFRACTION

To determine three refractive indices, α, β, and γ, on biaxial substances, mount material as usual. Find a grain which gives an interference figure with the acute bisectrix in the center of the field. Rotate the stage until the plane of the optic axes, the line joining the foci of the two hyperbolæ, is parallel to one or other of the vibration planes of the two Nicols. Test the relative refractive indices of the grain and the embedding oil for this position of the grain. Then proceed exactly as with isotropic substances, except that the grains must all have identical orientations, until an oil is found which has the same index as the grain in this position. With an identical orientation but with the plane of the optic axes 90° from the first position, measure, as above, a second index. One of these two indices, thus measured, will be β and the other may be either α or γ, depending on whether the grain is optically positive or negative. If the grain is positive the lower of the two indices is α and the higher β. If the grain is negative the higher of the two indices is γ and the lower β. In other words, the measurement made normal to the plane of the optic axis is β and the other is either α or γ as above. Two of the indices are thus known, β and α or γ. Working as near as possible on grains lying parallel to the planes of the optic axes, as approximately

determined by interference figures, proceed as above to determine two indices. One of these will be α and the other γ. The one already determined can be ignored, but the two determinations serve as a check. A grain lying normal to the obtuse bisectrix, as determined approximately by interference figures, gives β and either γ or α. This orientation is sometimes more convenient than that of grains lying parallel to the plane of the optic axes.

If the grains do not show any special tendency to lie in any one orientation, the statistical method can be used with some fair degree of certainty. Measure the lowest index shown by any grain in a given mount. This will be α. Then measure the highest shown by any grain. This will be γ.

A variation of this statistical method is to measure the highest and lowest, γ and α, indices of grains showing maximum double refraction. (See determination of amount of double refraction.)

The indices determined on the grains showing the emergence of the acute bisectrix in the center of the field are accurate. Those made on grains lying parallel to the plane of the optic axes and those lying normal to the obtuse bisectrix are subject to error, on account of the indefiniteness of interference figures used in identifying the orientation. Indices determined by the statistical method or its variation are always subject to the doubt as to whether the absolute highest and lowest indices have been found. There are cases, however, where only the statistical method is applicable. Any of the methods usually give results sufficiently accurate for ordinary determinative work. In fact, sometimes simply the mean refraction index, not necessarily β, is sufficient. But for work of high accuracy the measurements should be checked and rechecked, and the results tested by substitution in the formula

$$\tan^2 V = \frac{\alpha^2(\gamma^2-\beta^2)}{\gamma^2(\beta^2-\alpha^2)}$$

when V is half the optic axial angle and β, γ, and α are the measured indices. The calculation of V itself depends on the accurate measurement of β (see measurement of axial angle), but fortunately this measurement is of a comparatively high order of accuracy and the formula serves to check either α or γ of a much lower order of accuracy.

Occasionally, as has been said, the mean index of refraction is sufficient for ordinary determinative purposes. But, for purposes of record, the measured indices should always be definitely ϵ, ω, α, β, or γ, as the case may be, except of course in isotropic substances, where there is only one index. Indices measured without regard to orientation are usually worthless. There are cases, however, where it is practically impossible to obtain the proper orientation for the measurement of specific indices, such as are presented occasionally by rare substances fixed in one unsuitable orientation in a permanent mount. There are other cases where the worker has not the time to measure the specific indices, and there are still other cases where, for the purpose in hand, it is not essential that the particular worker should have the specific indices. In all such cases, indices should be given with some reference to the orientation in which the measurement was actually made; for example, index parallel or normal to

elongation of crystal, index parallel to plane of optic axes with acute bisectrix so many degrees from center of field, index parallel to c axis, index parallel to (111), index with optic axis (or acute bisectrix) emerging just out of field so many degrees to left of vertical cross hair, etc. Such data can scarcely be considered as publishable per se and are not always unambiguous, but they do have a value to the worker himself especially when working with substances which show a strong inclination to lie in particular positions.

Suitable substances for the demonstration of the foregoing are muscovite, potassium nitrate, ammonium nitrate, and aragonite.

Cases occur, especially with platy minerals, in which the grains persistently lie in one orientation. Sometimes, as with the micas, the acute bisectrix emerges nearly normal to the plate, and approximate values of β or γ can be measured directly. But another orientation is necessary for the measurement of the third index. It is possible, with patience and practice, to tilt even plates on their edges by judicious movements of the cover glass. This is naturally more easily done in viscous mounts. In order to give room for the grain to turn over, crushed glass may be mixed with the preparation. The glass particles, if not too small, support the cover glass, thus leaving the plates free to move. If the plate will not remain edge up, it is possible by quick observation to compare its index with that of oil as the plate passes through the vertical position.

Rod-shaped crystals present similar difficulties of orientation. The orientation can be altered by simply rolling the rods. Crushing frequently enables one to find fragments end up. But changing the orientation of any particles which have decidedly different dimensions is likely at any time to tax one's patience and ingenuity.

The refractive indices as measured must be consistent with the other optical properties. If a uniaxial substance is optically positive with the quartz wedge, gypsum plate, or quarter-undulation plate, ϵ must be greater than ω. If the substance is optically negative, ω is the greater. If a biaxial substance is optically positive, $\gamma - \beta$ must be greater than $\beta - a$. If the substance is negative, $\beta - a$ must be greater. If the substance shows strong double refraction, two at least of the indices must be considerably different. Furthermore, in all cases the double refraction, as actually measured, must check with the numerical difference of the indices involved. If the optic angle is small, two of the indices must be very close together and both quite different from the third index.

INTERFERENCE FIGURES

CONVERGENT LIGHT IN CRYSTALS

Convergent light when transmitted through crystals under certain conditions, which will be discussed below, is modified by interference phenomena (p. 14) and as a result shows very beautiful figures, usually called interference figures. These figures are of fundamental importance. Under suitable conditions they are produced by all crystals other than those belonging to the isometric system. Their absence therefore is an indication that the given crystal belongs to the isometric system. One type of figure is characteristic of the tetragonal and hexagonal systems, the uniaxial group, and

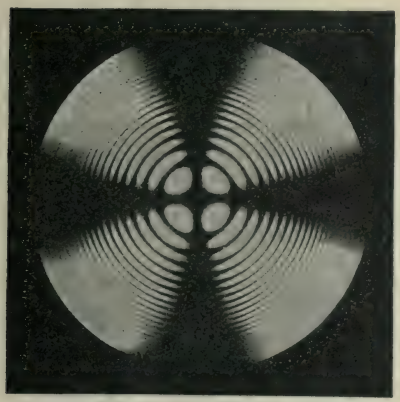
another type of figure is characteristic of the remaining systems, the biaxial group. Thus, direct observation of the absence of, or of the type of figure enables one to throw a given substance into one of three major groups, thus eliminating all substances in the other two groups. Determination of the optical character (p. 45) on the interference figure divides the uniaxial and biaxial groups each into two subgroups. Measurements on biaxial figures give the optic axial angles, and observations on the color distributions establish the character of the dispersion. Furthermore, the interference figure is the best and sometimes the only means of determining the orientation of a given crystal and therefore has a direct bearing on the measurement of refractive indices.

If a cone of light is passed through any given crystal, the effect of the crystal on the light depends on the crystal system to which the substance belongs, in other words, it depends on the character of the molecular packing in the crystal. Since the packing in isometric crystals is the same in every direction, substances belonging to this system show no special effect on the cone of light any more than that shown by a piece of glass or other amorphous substance. Quite distinct effects are shown, however, by substances in which the packing varies with the direction.

As previously explained, crystals may be divided into two groups, in addition to the isometric, according to the character of the space lattice. In the first group the packing is uniform in one direction, called the direction of the optic axis, and uniformly different from that of the optic axis in any direction at right angles to that axis. The optics of this group may be visualized roughly as a right circular cylinder, or accurately as an ellipsoid of revolution. In the ellipsoid of revolution the major axis represents the optic axis. All lines at right angles to this axis have the same length and the same optics. Substances belonging to the tetragonal and hexagonal systems have this structure. In the second group there are three directions in which the packing differs. The optics of this group may be visualized best by an oblate ellipsoid. Here there are two major axes and a third intermediate axis. Substances belonging to the orthorhombric, monoclinic, and triclinic systems have this structure.

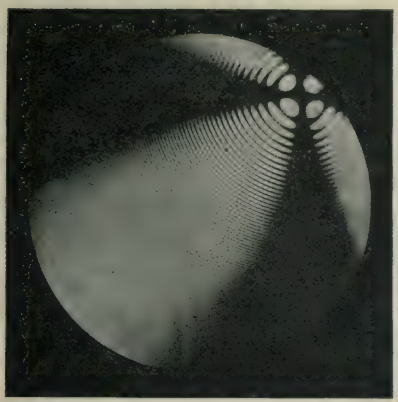
The first group having only one major axis is called the uniaxial group. The second group, having two major axes, is called the biaxial group. The distinction between these two groups is of fundamental importance. In practice, the distinction is made by observing the interference figures shown by the given substances. (Fig. 4.)

If a cone of light is passed through a uniaxial substance in a direction parallel to the optic axis of the substance, the rays at the center of the cone will strike the substance at right angles and will pass through without double refraction. All other rays, however, will be doubly refracted more and more as their angular distance from the axis of the cone is greater and greater. At any given distance from the axis the difference of path due to the double refraction will be the same, and the visible result, in the ideal case, will be a series of concentric circles showing a succession of colors in the Newton rings. The crossed Nicols cut out all light vibrations parallel to their planes, and consequently the series of concentric

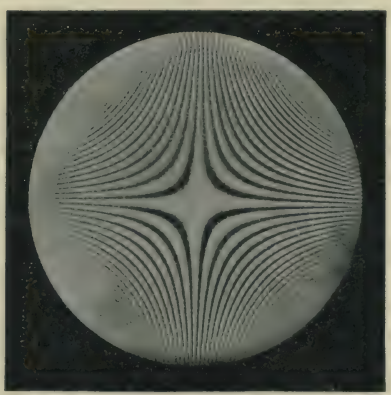


A

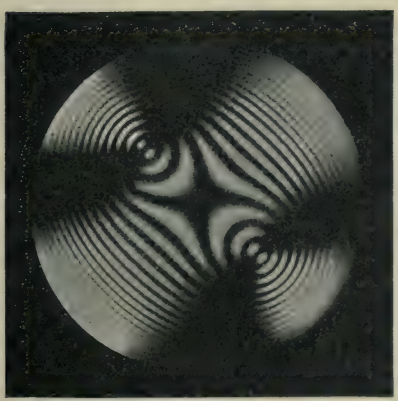
B



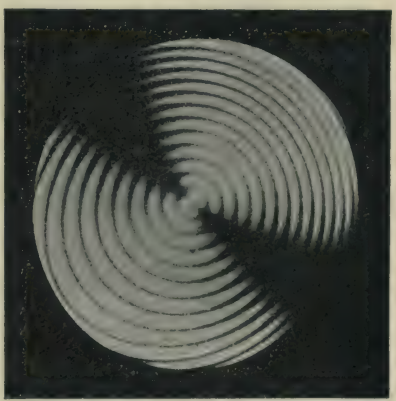
C



D



E



F

FIGURE 4.—A, Interference figure of uniaxial crystal (calcite), with optic axis vertical; B, same, with optic axis tilted from vertical; C, same, with optic axis tilted almost to edge of microscope field; D, same, with optic axis horizontal; E, interference figure of biaxial crystal (aragonite), with acute bisectrix vertical; F, interference figure of biaxial crystal (topaz), with optic axis vertical

From Johannsen's Manual of Petrograpric Methods, New York, 1918. Courtesy of McGraw-Hill Book Co. (Inc.).

circles is broken by a black cross. (Fig. 4, A.) The center of the cross is coincident with the center of the rings and is on the optic axis. If the axis of the cone of light and the optic axis are parallel, the center of the cross is in the center of the field of the microscope. As the stage of the microscope is revolved, no change whatever takes place. If the optic axis and the axis of the cone are slightly inclined to each other, the center of the cross will be slightly outside the center of the microscope field (fig. 4, B and C) and will describe a circle around the center of the field as the stage is rotated. As the mutual inclination of the optic axis and the cone axis becomes greater and greater, the center of the cross is farther and farther from the center of the field and describes a greater and greater circle as the stage is rotated. When the mutual inclination is sufficiently great, the center of the cross is no longer within the field, and only the straight bars of the cross are visible. These pass successively across the field of the microscope at right angles to each other as the stage is rotated.

The limiting case is that in which the optic axis of the substance is at right angles to the axis of the cone. (Fig. 4, D.) Not only the center of the cross but the bars also are no longer visible. The whole figure is rather indistinct.

As the stage carrying the mineral is rotated, there are certain positions in which two hyperbolæ will flash into the field from opposite quadrants, arrange themselves cruciform, and then quickly disappear in adjacent quadrants. As the rotation of the stage is continued, presently the phenomena of the hyperbola are repeated in the next quadrant. In a rotation of the stage through 360°, these phenomena occur four times, with a duration in each quadrant amounting to about 10° rotation (*11, p. 36*).

The optic axis is in the direction of the line separating the entering and departing hyperbolæ.

If a cone of light is passed through a biaxial crystal, the phenomena are much more complicated. There are four important directions in biaxial crystals which it is perhaps well to consider separately. The first is the direction of the acute bisectrix, that is, the direction of the line bisecting the acute angle formed by the two optic axes of the crystal. The second is the direction of the obtuse bisectrix; that is, the direction of the line bisecting the obtuse angle formed by the two hyperbolæ. The third direction is that of the optic normal; that is, the direction of a line perpendicular to the plane formed by the two optic axes. The fourth direction is that of an optic axis.

If a given biaxial crystal has an optic angle (acute angle between the two optic axes) not too large to be included in the field of the microscope, and if a cone of light be passed through the crystal parallel to the acute bisectrix, the crystal being rotated until its axial plane is parallel to the plane of vibration of one or other of the two Nicols, a dark cross will be seen, as in the case of a uniaxial crystal. But instead of the colored circular rings around the center of the cross, there will be two sets of roughly elliptical rings with their centers on the same bar but on opposite sides of the center of the cross. Toward the cross center these two sets of rings have a tendency to merge and together form a shape suggestive of a dumbbell. If the crystal is so thin or so slightly doubly refracting that the colored rings do not appear, the figure is the same as that of a uniaxial crystal, so long as the position of the grain remains un-

changed. But if the stage is rotated the resemblance immediately ceases. The cross breaks up into two hyperbolæ, their foci being the two centers, "eyes," of the colored rings. These hyperbolæ reach their maximum distance apart when the rotation has reached 45°. (Fig. 4, E.) As the rotation is continued they gradually approach each other and again form a cross at 90° rotation. The distance of the two foci from each other is a measure of the optic axial angle, as will be explained later. Certain substances have such large axial angles that both foci can not be seen in the field at the same time.

If the cone of light passes through the crystal parallel to the obtuse bisectrix, the phenomena are much the same in principle as when the light is transmitted parallel to the acute bisectrix. But the obtuse angle is too great to allow the foci to enter the field. On rotation of the stage the two hyperbolæ enter the field, form a cross, then open and depart from the field. The hyperbolæ formed when the light is transmitted parallel to the obtuse bisectrix are vague and undefined in comparison with those formed when the light is transmitted parallel to the acute bisectrix.

If the cone of light passes through the crystal parallel to the optic normal, the interference figure obtained is similar to that given by a uniaxial crystal when the light is transmitted perpendicularly to the optic axis.

If the cone of light passes through the crystal parallel to an optic axis, the interference figure is the same as that which would be obtained if the light were transmitted parallel to the acute bisectrix, except that one of the foci of the hyperbolæ, instead of the center of the cross, is in the center of the field of the microscope. (Fig. 4, F.) If the axial angle is sufficiently large, the other focus will be outside the field. The hyperbola whose focus is in the center of the field becomes a straight line when the stage is rotated to a position in which the axial plane of the crystal is parallel to the vibration plane of one or the other of the Nicols. A 45° rotation of the stage brings the hyperbola to its maximum curvature, and in this position its convex side is toward the acute bisectrix. The greater the optic axial angle, the less is the curvature of the hyperbola. Crystals are sometimes found in which the axial angle is so great that the curvature of the hyperbola is no longer perceptible in any position. So far as can be detected by the eye, the hyperbola is simply a straight line revolving around its center in a direction opposite to the direction of rotation of the stage. Since no curvature can be detected, it is impossible to ascertain from the figure the direction in which the acute bisectrix lies.

Generally speaking, one does not often find crystals of either uniaxial or biaxial substance, which lie on the microscope slide in exactly one of the positions described above. Usually the position of the grain is somewhere intermediate between some pair of the positions described, and the interference figure shows itself naturally as a combination of the phenomena given by the two positions. It is well to conceive of the whole phenomena of interference figures as simply a gradual change of appearance as the observed crystal is tilted or rotated from one position to another, and it is absolutely indispensable to realize that the phenomena are three dimensional and not two dimensional. When working with uniaxial crystals or

with biaxial crystals of very small axial angle, it is well to consider the uniaxial figure as simply the limiting case of a biaxial figure as the axial angle approaches zero. There are biaxial crystals, for example, biotite, in which the axial angle is so small that the interference figure is indistinguishable from the uniaxial cross.

The colored curves of both the uniaxial and biaxial figures depend both on the thickness of the crystal examined and on its degree of double refraction. Very thin grains of only slightly doubly refracting crystals do not show the colored curves. This lack, however, is not usually particularly important, since the black cross and the hyperbolæ are the essential phenomena to be observed.

To obtain an interference figure, use a high-power objective, about 4 mm, center the objective carefully, move the microscope slide until the crystal to be examined is at the intersection of the cross hairs, that is, in the center of the field, focus on the crystal, cross the Nicols, raise the condenser as high as possible, and remove the ocular. The figure should then be visible. A pinhole cap for the tube of the microscope aids visibility by cutting out side light. Another method is to leave the ocular in and to insert a Bertrand lens in the tube of the microscope in the slot provided for it. The figure thus obtained is much larger than that obtained when the ocular is removed, but it is also blurred. Which method to use is perhaps a question of personal preference, depending on whether one prefers to observe a clear small figure or a large hazy one. It is a fact, however, that figures difficult to obtain are more apt to be visible when the ocular is removed.

There is usually no difficulty in interpreting an interference figure if the emergence of an optic axis (the foci of the hyperbolæ or the center of the uniaxial cross) or the emergence of the acute bisectrix is within the field of the microscope. If the interference figure is a cross which remains a cross with no separation into hyperbolæ during a complete rotation of the stage, then the crystal is in all probability uniaxial. It should be borne in mind, however, that there is a possibility that the crystal is biaxial with an imperceptible axial angle. If the interference figure alternately forms a cross and breaks up into hyperbolæ as the stage is revolved, there is no doubt that the crystal is biaxial. If two apparently straight bars cross the field alternately and at right angles to each other, the crystal is probably uniaxial, but may be biaxial with a very perceptible axial angle, as could be seen if the emergence of the acute bisectrix were visible. If two dark curves alternately cross the field as the stage is rotated, the crystal is probably biaxial but may be uniaxial with the emergence of the optic axis tilted considerably out of the field.

Practically all these doubts may be settled by changing the position of the crystal on the slide. To do this requires considerable skill and patience and presupposes a mount in which the individual crystals do not adhere to the slide, to the cover glass, or to each other. Tapping and jiggling the cover glass with the point of a pencil are remarkably effective. In order to allow room for a crystal to turn over, it is sometimes helpful to mix crushed glass with the substance to be examined. If the glass particles are considerably larger than the crystals, they support the cover glass and allow

ample room for the tilting and turning of individual crystal particles. Most of the time, however, it is perhaps easier and quicker to search for another crystal lying in a more suitable position.

This search need not necessarily be a blind series of trials. If the Nicols are crossed, any given particle which remains perfectly dark during a complete rotation of the stage is either isotropic or will give a practicable figure. Likewise, any given particle which remains bright during a complete rotation of the stage between crossed Nicols will probably give a practicable figure. On the other hand, particles which alternately and distinctly change from perfect darkness to brilliancy as the stage is rotated between crossed Nichols will probably not give practicable figures, and, if necessary, should have their positions changed.

Rounded grains of quartz furnish examples of almost all forms of uniaxial figures and can be readily tilted or rolled from one orientation to another. Mica is one of the most difficult substances to tilt and should be used for practice.

OPTICAL CHARACTER

After having ascertained the uniaxiality or biaxiality of a given particle by observation of its interference figure, it is convenient to use the same figure for the determination of the positive or negative character of the crystal, and thus subdivide each of the two major groups into two subgroups.

If, in uniaxial crystals, the extraordinary ray is the faster ray, that is, if $\epsilon<\omega$, the crystal is defined as optically negative. If the ordinary ray is the faster, that is, if $\epsilon>\omega$, the crystal is defined as optically positive.

If, in biaxial crystals, the direction of vibration of the slow ray is the acute bisectrix, the crystal is defined as optically positive. If the direction of vibration of the fast ray is the acute bisectrix, then the crystal is defined as optically negative. In general, it may be stated as a close approximation that the crystal is positive if $\gamma-\beta>\beta-\alpha$, and negative if $\gamma-\beta<\beta-\alpha$. This relationship of the refractive indices should be used merely as a check and not as an actual determination except when no other means are readily available. It should be borne in mind that it is perfectly possible for a given crystal to be positive with one wave length of light and negative with some other wave lengths.

There are three convenient methods for the determination of the optical character of a crystal; the quarter-undulation mica-plate method, the quartz-wedge method, and the selenite-plate method.

To use the quarter-undulation mica plate, find or place the crystal in such a position that the optic axis emerges in the field somewhere near the center. In other words, obtain an interference figure showing the center of the cross nearly in the center of the field. Insert the quarter-undulation mica plate in the tube of the microscope in the slot provided for the purpose. The dark cross of the interference figure will disappear, and a dim white cross will take its place. Two dark spots appear in opposite quadrants. With negative interference figures the two dark spots lie along the direction of the slow ray of the quarter-undulation mica plate. With positive crystals the two dark spots lie along the direction of the fastest

ray of the mica plate. If colored rings are present in the interference figure, they are disjoined into four quadrants, those in the two opposite quadrants appearing to be removed outward from the center of the figure and those in the two other opposite quadrants appearing to be removed toward the center. The pairs of opposite quadrants in which both the ring phenomena and the dark spots appear may be reversed with different plates or in different microscopes, depending on the way in which the mica plate is mounted and on the direction of the slot in the tube of the microscope. Each microscope and mica plate should be calibrated once for all by observing the phenomena given by the particular microscope with the particular plate on an interference figure of a crystal of known optical character. Muscovite is optically negative, and its acute bisectrix lies almost perpendicular to the cleavage plane. Since a flake of this mineral lies flat on its cleavage plane on the microscope slide, it gives a good interference figure with a minimum of manipulation. It is not even necessary to prepare a slide. The cleavage piece may be placed directly on the stage of the microscope with equally good results. For these reasons a flake of muscovite serves as an excellent test piece for the calibration.

The quartz wedge (p. 24) is especially useful on highly colored interference figures. Ideally, one should use the wedge on crystal mounts which show the emergence of the optic axis of uniaxial crystals or of the acute bisectrix of biaxial crystals. Obtain the cross of the uniaxial figure, or, if the crystal is biaxial, rotate the stage until the hyperbolæ coalesce to form a cross. Insert the quartz wedge, thin end foremost, in the slot of the tube of the microscope. As the quartz wedge advances, the colored curves in two opposite quadrants of the figure will move in toward the center, and the curves in the two other opposite quadrants will move outward from the center. The appearance is as if the colors were pouring into the center of the figure from two opposite directions and were pouring out of the center in two opposite directions at right angles to the first two directions. As the wedge is withdrawn the phenomena are reversed. Since the colors reach higher and higher orders of Newton's color scale as thicker and thicker portions of the wedge pass over the field, it is well to insert the wedge always thin edge foremost and to confine one's attention to the color movements during the insertion. Furthermore, one thus avoids the possibility of errors due to misinterpretation of the color movements. With the same wedge and the same microscope the colors will always move inward in the same pair of opposite quadrants and outward in the other pair for positive crystals and the reverse for negative crystals. It is therefore sufficient to note the color movements produced in a particular microscope by a particular wedge on an interference figure of known optical character in order to have that combination of instruments calibrated for all time. Here, again, a cleavage flake of muscovite serves as an excellent test piece. The flake should be comparatively thick. Otherwise, the colored rings will not show up very well.

The essence of the phenomena produced by the quartz wedge on an interference figure is that in any particular quadrant of the figure the color movement is always the same for crystals of given optical character. Therefore it is not necessary that the crystal be accu-

rately orientated. Uniaxial figures with the center of the cross entirely out of the field of the microscope still show by the direction of bars the general position of the emergence of the optic axis. If this position is conceived as the center of the figure, the positions of the bars determine whether one is observing the upper right, upper left, lower right, or lower left quadrant. If the quartz wedge is inserted and the movement of the colors in the quadrant noted, the optical character is determined. The same holds for biaxial crystals, except that the acute bisectrix, although perhaps entirely out of the field, must be conceived of as the center of the figure. The hyperbolæ are convex toward the acute bisectrix. This fact locates the direction of the acute bisectrix and therefore determines the quadrant under observation.

Very thin particles and particles with very low double refraction do not show interference figures with colored curves, and therefore the quartz wedge is not usually satisfactory with this type of material. The selenite plate, on the other hand, although not well adapted to particles which show interference figures with colored curves, is particularly suitable for interference figures without colored curves.

The selenite plate, sometimes called the sensitive-tint plate, the red or violet of the first-order plate, or the unit-retardation plate, is a plate of gypsum so cut as to give a red or violet interference color of the first order. If such a plate is placed over an interference figure showing the dark cross, two opposite quadrants of the figure will become blue and the other pair of opposite quadrants will become yellow. This phenomenon is best seen in a uniaxial interference figure, showing the emergence of the optic axis, or in a biaxial figure, with the crystal rotated to the position where the hyperbolæ form a cross and the acute bisectrix emerges in the field of view. But, as in the case of the quartz wedge, it is not necessary that the optic axis or the acute bisectrix emerge within the field. The coloration of the different quadrants is the essential part of the phenomenon. As has been previously explained, the quadrants can be identified in the case of a uniaxial figure by the relative positions taken by the dark bars as the stage is rotated and, in the case of biaxial figures, by the direction of convexity of the hyperbolæ. Knowing the particular quadrant under examination, one has simply to note the color given to this quadrant by the selenite plate. The opposite quadrant, whether it is invisible or not, will be similarly colored, and the other pair of quadrants will be colored differently from this first pair.

To use the selenite plate, first obtain an interference figure, preferably showing the emergence of an optic axis or of an acute bisectrix. If the figure is biaxial, rotate the stage until the hyperbolæ form a cross. If it is not convenient to obtain figures showing the emergence of the optic axis or of the acute bisectrix, identify the quadrant under observation. Insert the selenite plate in the tube of the microscope in the slot provided for the purpose, and note the color given.

It is not absolutely necessary to rotate the biaxial figure until the cross is formed. If, for example, the figure is in the 45° position, in which the hyperbolæ are at their maximum separation, the con-

cave sides of the hyperbolæ will become similarly colored and the convex sides will show the other color. The quadrant principle, however, still holds and is perhaps the easiest way to remember the color relationships.

Which of the two colors, blue or yellow, will appear in a given pair of quadrants depends on the mounting of the plate and on the direction of the slot in which the plate is inserted. As is the case with both the mica plate and the quartz wedge, it is necessary to calibrate each selenite plate with each microscope. Here again a cleavage flake of muscovite (optically negative) is almost an ideal test piece. Since interference figures showing colored curves are not desired, the flake should be comparatively thin.

Certain microscopes have a selenite plate attached to the substage mechanism between the polarizer and the condenser. The effect is the same as if the plate were inserted in the microscope tube in the same direction. These microscopes also usually have a slot in the tube for the insertion of another selenite plate. One can choose which he desires to use. It should be remembered, however, that if the plates are mounted similarly, the color effects will be reversed if the insertion directions are at right angles and that if the plates are mounted dissimilarly the color effects will be the same if the insertion directions are at right angles; that similarly mounted plates will give the same color effects when inserted in the same direction; and that dissimilarly mounted plates will give opposite color effects when inserted similarly. It is usually easier on the memory and much more convenient practically to use one plate in one direction exclusively. Any doubt that may arise as to the interpretation of the colors can be immediately settled by test on any substance of known optical character, muscovite being about the most convenient.

Optical character can be studied on any crystal giving a good interference figure. Those crystals suggested for interference figure observations serve admirably for optical character determinations.

OPTIC-AXIAL ANGLE

Optic-axial angles, although sometimes variable, frequently serve as a ready means of distinguishing between two or more substances of the same group or subgroup. This is especially true when the angles are widely different. The optic-axial angle is the acute angle formed by the two optic axes. The apparent angle when measured in air is denoted by $2E$. The true angle is denoted by $2V$. When measured in oil or water the apparent angle is denoted by $2H$.

The true axial angle, $2V$, can be calculated from the values of the three refractive indices, provided these latter are known with sufficient accuracy.

If the crystal is optically negative,

$$\tan^2 V = \frac{\alpha^2(\gamma^2 - \beta^2)}{\gamma^2(\beta^2 - \alpha^2)}.$$

If the crystal is optically positive,

$$\tan^2 V = \frac{\gamma^2(\beta^2 - \alpha^2)}{\alpha^2(\gamma^2 - \beta^2)}.$$

It should be noted that, since the acute optic angle is $2V$, both the formulas give angles which must be doubled in order to obtain the true axial angle. Refractive indices are measured under the microscope to only about the third decimal. For a large number (perhaps most) of crystals this is not a sufficient degree of accuracy to enable the axial angle to be calculated other than approximately. The formulas should therefore be used for the calculation of the axial angle only as a check or when no other means of obtaining the angle are available. As a matter of fact, the formulas are more likely to be of use as a check on the index measurements than as a check on the angle measurements.

The curvature of the hyperbolæ gives a rough indication of the size of the optic-axial angle. If the interference figure shows the focus of one of the hyperbolæ nearly in the center of the field, and if the hyperbola itself is apparently a straight line when the figure is turned to the 45° position, the axial angle is nearly 90°. As the axial angle becomes smaller the curvature of the hyperbola becomes greater. A relatively small amount of experience will enable one to make a rough estimate of the axial angle from the hyperbola curvature, which in certain cases will be sufficiently accurate. For example, certain minerals have very variable axial angles, and an approximation within the limits of variation is sufficient for ordinary determinative purposes, provided the other optical constants can be determined satisfactorily.

Perhaps the most generally used method for the actual measurement of the optic-axial angle resolves itself simply into a measurement of the distance between the two foci of the hyperbolæ. For this purpose interference figures should be obtained which show the emergence of the acute bisectrix at, or very nearly at, the center of the field. If the emergence of the acute bisectrix is much out of the center, the distance measured between the two foci will not be the true distance, and consequently the true axial angle will not be obtained. Furthermore, it is essential that both foci of the hyperbolæ appear in the field. After a suitable figure has been obtained, it is rotated to the 45° position, where the separation of the hyperbolæ is at a maximum, and the distance between the two foci is measured with an ocular cross-grating micrometer.

If a series of such measurements are made on crystals of different known optic-axial angles, a chart can be constructed by plotting distances against angles. By interpolation on this chart any distance measured between the foci can be converted to terms of optic-axial angles. There are many refinements of this method, but the essentials are as given above. It should be borne in mind that the chart so constructed holds only for the particular combination of lenses and micrometers used in its construction. Furthermore, one should not confuse $2E$ and $2H$.

The relationship between $2E$ and $2V$ is given by the formula

$$\sin E = \beta \sin \gamma,$$

that is, the sine of the apparent optic-axial angle measured in air is equal to the intermediate index of refraction multiplied into the

sine of the true axial angle. It is perhaps more convenient to state the formula as

$$\sin V = \frac{\sin E}{\beta}$$

this is, the sine of the true optic-axial angle is equal to the sine of the apparent axial angle divided by the intermediate index of refraction. Thus, if the apparent axial angle in air is measured and the β index is known, the true axial angle can be calculated.

A very good method for measuring the apparent optic-axial angle by measuring the distance between the two foci of the hyperbolæ is symbolized by the formula:

$$\sin E = \frac{D}{K}$$

in which D is half the distance between the points of emergence of the optic axes and K is a constant which must be determined once for all for any lens combination. To determine this constant it is best to use a number of crystals of known and differing axial angles and to take the mean as the most nearly correct value for K. With this constant once determined, one has only to divide it into a particular distance reading in order to obtain the sine of half the apparent axial angle. This is one of the most satisfactory methods known.

The optic-axial angle varies for different wave lengths of light. Consequently, for very accurate measurements, light of known wave length should be used. Most of the angles given in the literature, however, are for white light, and for ordinary purposes this is sufficient. Even if the angles should be measured in monochromatic light, their values for white light should be given also, as in ordinary determinative work it is not always convenient to use monochromatic light.

The micas, potassium nitrate, aragonite, and calcium nitrate are suggested as objects for axial angle measurements.

DISPERSION OF OPTIC AXES

Ordinarily, isotropic substances—a glass prism, for example—deflect light rays according to their wave length. The red, with the greater wave length, will appear at one end of the spectrum, and the blue, with the lesser wave length, will appear at the other end. The red will be less deflected from the original direction of the light rays than will the blue. The actual amount of deflection for either the red or the blue, or for any other color, will depend on the relative refractive indices of the deflecting body and its surrounding medium. The greater the difference of the refractive indices of the deflecting body and its surrounding medium the greater will be the deflection. Since a beam of light consisting of different wave lengths, each of which is differently deflected, can be spread over a screen as a spectrum, we speak of the light having been dispersed. From what has just been said above, it is obvious that in isotropic bodies which include isometric crystals, the dispersion will always be less for the red than for the blue. The fact of dispersion is therefore of no special determinative importance in ordinary work on isometric crystals.

With doubly refracting crystals the case is different. Any double-refracting crystal is a dispersive body with a refractive index which varies, often considerably, with different directions in the crystal.

In any given mounting medium the dispersion for any given wave length of light will therefore vary with the direction in the crystal in which the light is propagated. Consequently, it happens in certain uniaxial crystals, tetragonal or hexagonal, which have their ordinary and extraordinary refractive indices very close together, that the extraordinary-ray direction is the vibration direction of the slow ray for light of one wave length and is the vibration direction of the fast ray for light of another wave length, or vice versa. Thus the crystal may be optically positive for light of one wave length and optically negative for light of another wave length. Ordinarily, the dispersion of uniaxial crystals is of no special determinative importance, but it is essential to realize that the basically important determination of positive or negative optical character may be reversed by a change in the color of the light used.

Biaxial crystals, that is, crystals belonging to the orthorhombic, monoclinic, or triclinic systems, have dispersions which are characteristically different for each of the three systems. Observation is made on an interference figure which shows the emergences of the optic axes and also the colored rings surrounding the points of emergence. The distribution of the colors is spoken of as resulting from the dispersion of the optic axes. The relative positions of the red and violet rays are to be noted, all other colors being neglected. Sometimes the red is dispersed more and sometimes less than the violet. This is customarily expressed as $\rho > v$ or $\rho < v$, as the case may be; that is, the dispersion of red is greater or less than that of the violet.

Interference figures given by crystals of the orthorhombic system are symmetrical to two planes at right angles to each other. One of the planes is the plane of the optic axes which, of course, contains both optic axes and the acute bisectrix. The other plane passes through the acute bisectrix and is at right angles to the first plane. Put more simply, perhaps, the figures given by orthorhombic crystals are symmetrical to the line joining the foci of the two hyperbolæ and also symmetrical to a line at right angles to this line and passing through the acute bisectrix. The dispersion of any particular crystal is always least for that color which lies immediately adjacent to the concave sides of the hyperbolæ, and greatest for that color which borders the convex sides of the hyperbolæ. It is best to rotate the figures to the 45° position when observing the positions of these colors. In some few cases a change in the wave length of the light used may change the position of the plane of the optic axes to a new position at right angles to the first. This is called crossed axial plane dispersion. In such cases the crystal will be uniaxial with light of some intermediate wave length. Crystals showing crossed axial plane dispersion give very complicated figures with white light, owing to the fact that the figures are the resultants of all the superposed figures formed by the various color components of the white light.

Monoclinic crystals present interference figures which have only one plane of symmetry, instead of two, as in the orthorhombic sys-

tem. There are three possible cases: (1) Inclined dispersion of both bisectrices; (2) horizontal dispersion of the acute bisectrix, and (3) crossed dispersion of the obtuse bisectrix.

Inclined dispersion of both bisectrices simply means that the bisectrices of both the acute and obtuse optical angles differ in direction by some angle for different wave lengths of light. It is always accompanied by a dispersion of the optic axes. The interference figure is symmetrical to the plane of the optic axes. That is, it is symmetrical to a line joining the foci of the two hyperbolæ. But it is not symmetrical to a plane at right angles to the plane of the optic axes, as is the case in the orthorhombic system. Crystals, therefore, belonging to the orthorhombic system can be distinguished from crystals belonging to the monoclinic system and showing inclined dispersion of the bisectrices by simple inspection of the interference figures. The crystal is orthorhombic if the interference figure has two planes of symmetry and monoclinic if it has only one plane of symmetry. In monoclinic-interference figures showing inclined dispersion of the bisectrices, the colored curves around the foci of the hyperbolæ will differ in size and somewhat in shape at the two foci. There is a tendency for the curves to be more elongated near one focus than near the other. Also, the colors around one focus will be more intense than those around the other, and in a different sequence. Usually the relative dispersion of red and violet is shown as with orthorhombic crystals, but if the dispersion of the bisectrices and the optic axes is very great, the relative positions of the red and violet in relation to the hyperbolæ may be reversed at the two foci. Red may lie on the concave side of one hyperbola at the focus and violet on the concave side of the other hyperbola at its focus. Fortunately, the high dispersion which brings about this condition is not common.

Horizontal dispersion of the acute bisectrix means that, with a change in the wave length of the light used, the position of the interference figure will change into a new position parallel to the first. In other words, the plane of the optic axes will appear, in the interference figure, to be shifted in a direction at right angles to itself. Thus, the use of the spectrum colors in order will shift the interference farther and farther from its initial position. This change in position can not, of course, be seen when white light is used exclusively. Color screens can be used in the substage of the microscope. If white light is used, the stage should be rotated until the principal sections of the interference figure are parallel to those of the Nicols, or until the cross is formed. It will then be noticed that the dark bar passing through the two foci, both at the top and at the bottom, will be bordered by different colors. Here again there is only one plane of symmetry.

Crossed dispersion of the obtuse bisectrix means that if successively greater and greater or less and less wave lengths of light are used, the interference figure will appear to rotate about its center.

In white light the distribution of colors in the two melatopes (foci of the hyperbolæ) differs from right to left and from top to bottom. The colors occur in inverse order, so that if the figure is rotated through 180° about the acute bisectrix, each melatope will occupy the position previously held by the other, and the color distribution will be exactly the same as before. When the inter-

ference figure is in parallel position so that its bars coincide with the principal planes of the Nicols, the black cross is unsymmetrically bordered by colored bands. That is, the upper left and lower right sides are bordered by one color, and the upper right and lower left by another (7).

Triclinic crystals give interference figures which are entirely unsymmetrical. This can best be seen when the emergence of the acute bisectrix is in the center of the field.

MEASUREMENT OF DOUBLE REFRACTION (BIREFRINGENCE)

Double refraction is, of course, confined to crystals which have different degrees of ease of vibration (different refractive indices) in different directions. Isometric crystals normally have no double refraction, or it may be said that their double refraction is zero. Certain crystals have such low double refraction that it can barely be detected. There are still other crystals which have extremely high double refractions, so much so that the difference in refractive indices in different directions in a given crystal is often much greater than the difference between the refractive indices of some chemically entirely distinct crystals. Between the barely perceptible and the extremely high double refractions there is a whole series of intermediate double refractions. The measurement of double-refraction values is, therefore, very useful as a means of identification of crystalline substances.

The maximum double refraction of any given crystal is expressed simply as the arithmetical difference between the highest and lowest refractive index of the crystal. Thus the maximum double refraction of a uniaxial crystal is $\epsilon-\omega$ or $\omega-\epsilon$, according to whether ϵ or ω is the greater. Likewise, the maximum double refraction of a biaxial crystal is $\gamma-\alpha$. Since biaxial crystals have three indices of refraction, there is also the double refraction denoted by $\gamma-\beta$ and $\beta-\alpha$, both of which are always less than the maximum for a given crystal. It follows, therefore, that if the refractive indices of a particular crystal are known with sufficient accuracy, the double refraction can be obtained by simple subtraction. It is almost always best, however, to obtain the double refraction by direct measurement, as the value so obtained serves as a mutual check on the refractive-index determinations.

Crystals of the same substance lying in random relationship to the direction of the light may show any degree of double refraction, ranging from zero to the maximum for that substance. The first essential, therefore, is to orientate the crystal so that it shows the particular double refraction desired, either the maximum of the $\gamma-\beta$ or of the $\beta-\alpha$.

Uniaxial crystals show their maximum double refractions when the crystals are so orientated that the optic axis lies parallel to the plane of the microscope slide. Stated conversely, they show their maximum double refraction when the optic axis is at right angles to the direction of light propagation. This orientation can be recognized as explained under uniaxial-interference figures. It is essential to search the mount for a particle already in this orientation or else turn a particle into it. Because of the fact that the optic axis of uniaxial crystals is usually parallel to the length of the crystal, it happens that a great many uniaxial substances show a natural

tendency to lie in the proper orientation for double-refraction measurements. So far as double refraction is concerned, this is a great convenience which, nevertheless, does not prevent the orientation from being the worst possible when interference figures showing the emergence of an optic axis are desired.

After a particle with the proper orientation has been found, it is rotated to extinction between crossed Nicols. It is then further rotated 45° either clockwise or anticlockwise. This brings it to a state of maximum illumination. A quartz wedge is then inserted, also in a 45° direction. As the quartz wedge advances, either one of two phenomena may take place. If the vibration directions of the fast ray of both the particle and the wedge coincide, then, as the wedge advances the interference colors will rise in the order in Newton's scale. Each new color will start in the interior of the particle and progress toward the edge. The reverse, of course, takes place as the wedge is withdrawn. On the other hand, if the fast-vibration direction of the quartz wedge coincides with the slow-vibration direction of the particle, or vice versa, the interference colors fall in the order in Newton's scale, each new color progressing from the edge of the particle toward its interior. If the first set of phenomena takes place, the particle should be rerotated back to extinction between crossed Nicols and then further rotated to a new 45° position at right angles to the first 45° position. It is not absolutely essential that the rotation be just as stated. It is essential, however, that the two 45° positions be approximately 90° apart. In this new 45° position the second set of phenomena will be observed as the quartz wedge advances. If the particle is of uniform thickness, the colors will fall in order until gray or black is reached. If the particle is not of uniform thickness the gray or black must be watched for in some particular predetermined spot of the particle, preferably its center. When the gray or black color is reached, the advance of the wedge should be stopped. The interference color given by the quartz wedge alone at this point should be noted. If there are vacant spots in the field, this interference color may be noted at these spots; otherwise it is necessary to remove the particle, possibly the whole slide. The wedge is then slowly withdrawn, and the order of the interference color noted by counting the number of times the color has appeared during withdrawal. The color and the order of the color are then known. The thickness of the particle is the only other essential. In the case of nonuniform thickness it is necessary to know the thickness at the point where the black appeared.

The interference color, the order of the color, and the thickness of the particle being known, reference should be made to the chart of double refraction of Michel-Lévy. (Fig. 5.) This chart is included in most textbooks of petrographic methods. In it the ordinates represent thickness and the abscissæ double refraction. To use it, simply follow the thickness line toward the right until the observed color of the ascertained order is reached. From this point follow the diagonal line upward and to the right to the edge of the chart. Here the double refraction will be found. It is of course obvious that the chart can be used backwards to determine the thickness if the double refraction is previously known.

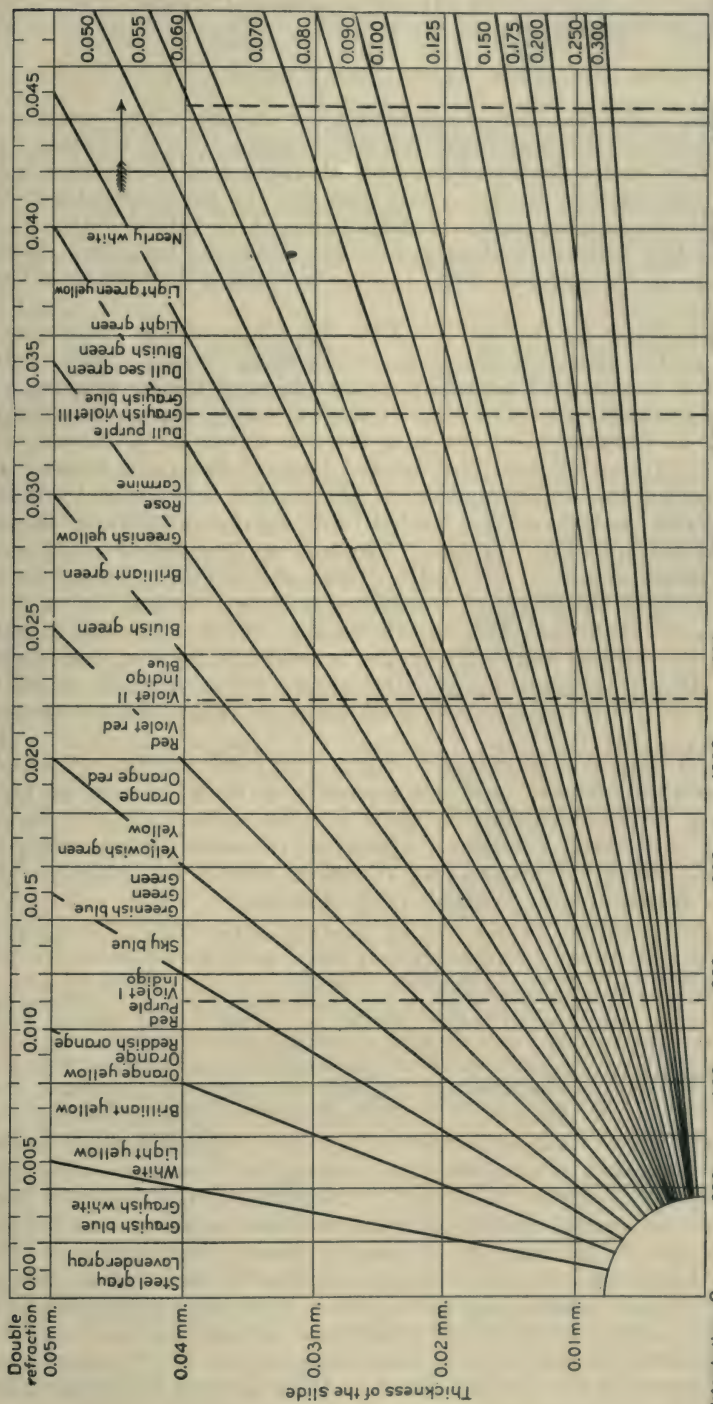


FIGURE 5.—Michel-Lévy chart of double refraction

The double refraction of a particle of a biaxial crystal in any orientation can be calculated from the formula:

$$\gamma' - \alpha' = (\gamma - \alpha) \sin \theta \sin \theta'$$

in which $\gamma' - \alpha'$ is the double refraction for the particular orientation in question, γ is the maximum refractive index of the crystal, α the minimum refractive index of the crystal, and θ and θ' are the angles, respectively, between the two optic axes and the perpendicular to the section of the crystal under examination. The values obtained by the use of this formula will vary, however, from the maximum double refraction of the crystal down to the minimum, depending on the orientation.

Crystals lying on the slide so that the plane of the optic axes is parallel to the plane of the slide, or, in other words, lying so that the light is transmitted normally to the plane of the optic axes, give the maximum double refraction of the crystal, $\gamma - \alpha$. This orientation can be identified by the interference figure as previously explained. After a properly orientated particle has been located, the procedure for the determination of the double refraction by means of the quartz wedge and the Michel-Lévy chart is exactly as already described for uniaxial crystals. Crystals so orientated as to show the emergence of a bisectrix in the center of the field give, under the same procedure, the double refraction corresponding to $\gamma - \beta$ or $\beta - \alpha$. Incidentally, these last two determinations can be checked qualitatively if the optical character of the crystal has been already determined. If the crystal is positive $\gamma - \beta > \beta - \alpha$; and if negative, $\gamma - \beta < \beta - \alpha$. This test does not hold, however, when the true optical angle, $2V$, is near 90°.

It is not always convenient to place a crystal particle in exactly the orientation desired, and consequently it is of interest to know something about the probable error in measurements made on imperfectly orientated particles. The error of course, varies with the degree of double refraction, and therefore differs for different substances. According to Wright (*20*), however:

> It may be assumed in general that the birefringence of a plate inclined at an angle of 5° to 10° with the true direction (optic normal or bisectrix) will be in error about 2 per cent of the true value for $(\gamma - \alpha)$, $(\gamma - \beta)$, or $(\beta - \alpha)$; an inclination of 10° to 15°, about 5 per cent, while for 15° to 20° inclination the error may be as much as 10 per cent of the correct value desired. . . . The actual error of such a determination should not exceed 10 per cent of the correct value of the birefringence of the section. The probability of finding a section making an angle within 10° of a particular direction is about 1 in 66; and a section within 20° about 1 in 16.

Whether the double refraction of a given crystal is high or low can be ascertained immediately by crossing the Nicols and observing the interference colors. The higher the order of the colors in Newton's scale the higher is the double refraction, and we should accustom our eyes to distinguish between, at least, high and low order colors. The very low order colors are usually dull grays, perhaps grading off into other dull colors. The very high order colors, on the other hand, are brilliant, sometimes so much so as to appear almost white. A microscopic slide made up of mixed quartz and calcite brings out the contrast between the high and low order colors very well and illustrates the ease with which highly doubly refract-

ing substances can be " spotted," even when occurring as very minute quantities admixed with substances of low double refraction. Unfortunately, the converse does not hold. Hunting for traces of a substance with a low double refraction when it is admixed with substances of high double refraction is apt to be a long and perhaps a fairly hopeless quest. This is owing partly to the fact that the brilliance of the high-order interference colors has a tendency to blind one to the low-order colors, but the relative hardness and solubility of the two substances also have their effects under certain conditions. If, for example, quartz and calcite are ground together, the calcite being the softer, has a tendency to adhere to and mask the quartz grains. Likewise, if sodium nitrate, $NaNO_3$, and gypsum, $CaSO_4 \cdot 2H_2O$, are crystallized together, there is a tendency for the very soluble and highly doubly refracting sodium nitrate to coat and thereby mask the less soluble and low doubly refracting gypsum. Exceptions could undoubtedly be found, but it seems to be a general rule that substances of high double refraction are more apt to mask substances of low double refraction than vice versa.

Another method for judging the relative degree of double refraction of a substance depends on the change in relief, that is, the change in visibility if any, of the particles as the stage is rotated. If calcite, for example, is mounted in an oil which has a refractive index very close to, but not exactly either the maximum or minimum index of the calcite, particles so orientated that they show the maximum double refraction (particles so orientated that the light is transmitted perpendicularly to the optic axis) will be barely visible in one position and will be more and more distinctly visible as the stage is rotated. Maximum relief will occur at 90° from the position of minimum relief, after which the relief will become less and less, as the stage is further rotated until another position of minimum relief is reached at 180° from the first position. If the stage is further rotated the relief will become greater up to 270°, and from thence will become less until the initial position is reached. In the case of a highly doubly refracting substance like calcite, mounted as stated, the change of relief on rotation of the stage is very great. At the positions of maximum relief the particles appear to stand out of the oil and to have dark shadows on their sides. The surfaces of the particles are distinctly visible, and most of the inclusions in the interior of the particles are invisible. In the position of minimum relief the exact opposite is true. The surfaces of the particles are not visible at all, only the horizontal outline being seen, and the inclusions stand out prominently. Intermediate positions between those of maximum and minimum relief give intermediate phenomena.

It should be borne in mind that particles so orientated that the light is transmitted parallel to the optic axis will show no change in relief as the stage is rotated, no matter how great the double refraction may be. As the particle is tilted out of this orientation the change in relief becomes more and more pronounced until the maximum is reached when the light is transmitted perpendicularly to the optic axis. If quartz is mounted in a similar way and the stage is rotated, it will be noticed that none of the particles shows a very great change of relief. At the most, the outline of certain

particles will be more distinct in certain positions as the stage is rotated. Thus, properly orientated particles of highly double refracting substances show a very great change of relief on rotation, and particles of substances with very low double refraction show very little change of relief. The change of relief on rotation is, therefore, a rough indication of the amount of double refraction. The phenomena will take place only in polarized light. The polarizer should, therefore, be in, but the analyzer should be removed.

The orientation of the particles can be ascertained by means of interference figures, as previously explained. It is, of course, obvious that if one is seeking for particles showing particular types of interference figures, the change of relief on rotation would be a fair guide. For example, in the case of calcite just described, those particles which showed great change of relief would not show an interference figure with the optic axis emerging in the center of the field, whereas particles showing no change of relief would probably give such a figure.

Suitable substances for the study of double refraction are calcite, quartz, sodium sulphate, and potassium sulphate.

EXTINCTION ANGLES

It has been previously explained that if an isotropic (amorphous or isometric) substance is placed between crossed Nicols and the stage rotated, the particles of the substance remain dark during the complete rotation of the stage, no matter what relationship the position of the particles may have in reference to the direction of the transmitted light. Except abnormally, such particles never light up between crossed Nicols, and therefore can not be said to extinguish. It may be said that every possible position of the particle is a position of extinction. For this reason no particular position has any especial significance. The fact that a given substance remains dark, in any orientation, during a complete rotation of the stage between crossed Nicols, simply indicates that the substance is amorphous, or isotropic, and nothing more. It is essential to remember, however, that crystals of some of the other systems in one orientation, that in which the light is transmitted parallel to the optic axis, behave as do isotropic substances. If this is suspected, the orientation of the particle under examination should be changed. If it still remains dark during a complete rotation of the stage it is certainly amorphous or isometric.

Except in the one case just noted, crystals of all the other five systems behave very differently when rotated between crossed Nicols. During a complete rotation they light up and then become dark (extinguish) four times. That is, during a complete rotation of the stage, there are four positions of maximum brightness and four positions of maximum darkness. As the stage is rotated from a position of maximum brightness, the brightness gradually fades until in the position of maximum darkness there is usually no light whatever visible through the crystal. These positions of maximum darkness are called the positions of extinction and have a very definite relationship to the structure of the crystal.

It will be recalled that in the tetragonal, hexagonal, and orthorhombic systems all the principal vibration directions of light are

parallel to the crystallographic axes. In the monoclinic system only one vibration direction coincides with a crystallographic axis, namely, the crystallographic axis b. The other two vibration directions may be anywhere in the plane determined by the crystallographic axes a and c. As a rule, neither of these two vibration directions is parallel to either of the two axes a or c. It is possible, however, for one of the vibration directions to be parallel to one of the axes, but since the angle between a and c is not a right angle in the monoclinic system and the angle between the two vibration directions is a right angle, it is impossible for both vibration directions to be respectively parallel to a and c in the same crystal. Stated briefly, in the monoclinic system, one of the vibration directions will be parallel to a crystallographic axis, another vibration direction will be inclined to the crystallographic axes, and the third direction may be either parallel or inclined, probably inclined, to the crystallographic axes. In the triclinic system it is possible for one and only one vibration direction to be parallel to a crystallographic axis, but usually all the vibration directions are inclined to all the axes.

The foregoing may be summed up in the statement that in the tetragonal, hexagonal, and orthorhombic systems every vibration direction is parallel to some crystallographic axis; in the monoclinic system two vibration directions, but probably only one, may be parallel to crystallographic axes, and in the triclinic system one vibration direction, but probably none, may be parallel to a crystallographic axis.

The vibration directions are shown by the positions of extinction of the crystal between crossed Nicols. The directions of the crystallographic axes may be determined by crystal edges when present or by cleavage lines. The extinction angle is simply the angle between the extinction direction and a crystallographic axis. Different orientations of the crystal, however, may give different extinction angles, and it is therefore necessary to find the orientation in which the angle between a given vibration direction and a given crystallographic axis is the maximum. Interference figures and double refraction observations should here be used as well as all the crystallographic information that can be obtained.

The procedure is comparatively simple. Be sure that the two Nicols are accurately crossed, that the cross hairs are parallel to the vibration directions of the Nicols, and that the objective of the microscope is accurately centered. Place the crystal so that a crystal edge, or a cleavage line, is parallel to one of the cross hairs. Read this position on the stage vernier. Rotate the stage until the crystal extinguishes. Then read the vernier again. The angle given by the difference of the two readings is the extinction angle. It is well to make a number of measurements in this way, then rotate the stage 180° and make a similar number of corresponding measurements. The average of all these measurements should then be taken.

In the measurements of extinction angles, and, in fact, in any work where a change in the orientation of a crystal is necessary or desirable, a universal stage will be found a very convenient accessory. It is not recommended; nevertheless, if a good universal stage is not available, a passable substitute may be contrived by grinding down the round knob of a broken bell jar or of a desiccator to hem-

ispherical shape. If this is set on its round side in the central opening of the ordinary microscope stage, and a crystal is stuck to its flat side by a drop of cedar oil, a considerable amount of tilting can be done with fair convenience. There are, of course, no means of reading angles except that furnished by the microscope stage for horizontal angles, but the contrivance is capable of yielding a considerable amount of qualitative information.

Probably the greatest source of error in the measurement of extinction angles lies in the difficulty of accurately determining the position of extinction. As has been said before, this position is simply the position of maximum darkness, and on both sides lie series of positions of only slightly less darkness. This is especially true in crystals of very low double refraction. In such crystals the position of maximum brightness yields merely grays of a very low order, and these grays fade out gradually into darkness as the stage is rotated toward a position of maximum darkness. It frequently happens in such cases that the stage may be rotated several degrees either way about the position of extinction without any easily perceptible change of illumination being noted. Furthermore, human eyes differ in their ability to detect slight differences in degree of darkness. A given eye may be more sensitive to a color change than to a change in degree of illumination.

If a colorless crystal, mounted in a colorless oil, is at the position of extinction between crossed Nicols, and a selenite plate is inserted in the tube of the microscope, both the crystal and the surrounding empty field will have exactly the same shade of color and, so far as color is concerned, will be indistinguishable. If now the microscope stage is slightly rotated so as to move the crystal slightly out of the position of extinction, the color of the crystal will change distinctly, and the empty field will remain of the same color as before the rotation. The crystal and the field will then stand out in strong contrast. As the stage is further rotated the contrast will increase until the position of maximum brightness is reached, and will then decrease until the colors of the crystal and the field again become identical at the next position of extinction, and so on, for a complete rotation. The quartz wedge can be used exactly in the same manner instead of the selenite plate and will give the same phenomena. One should be careful, however, in his choice of colors out of the whole series of colors given by the quartz wedge, since all colors are not equally sensitive. Violet, sometimes called the sensitive tint, or red of the first order, is the best color to use. This color is given by the selenite plate. Numerous adjuncts have been devised to render more accurate the determination of the position of extinction. Perhaps the best of these is the Wright biquartz wedge plate. This plate is placed in the focal plane of the ocular. Each half of the field is equally illuminated when the crystal is in the position of extinction. A very slight rotation of the crystal out of the position of extinction produces a marked difference in the illumination of the two halves of the field.

No single best method for determining the position of extinction can be prescribed. Natural color in a crystal, for example, may very well render any of the color methods inapplicable and force one to use some method involving degrees of illumination. Personal pecu-

liarities of vision may make one method more advisable for one individual than for another. Such decisions, of course, must be made by the individual worker.

The plagioclases, gypsum, hornblende, and asbestos serve very well for a study of extinction angles.

SIGN OF ELONGATION

Under the same conditions and when free to grow unimpeded, crystals of any given substance have an exceedingly strong tendency to take on characteristic forms. Thus mica is flattened parallel to a basal plane of the crystal, and apatite is elongated parallel to the prism edges, that is, parallel to the c axis of the crystal. The relationship between the direction of elongation of a crystal and the vibration directions in the crystal is sometimes of determinative value. This relationship is expressed as either positive or negative, and the elongation of the crystal is spoken of as positive or negative. If the elongation of the crystal is parallel to the fast ray, the elongation is negative. If the elongation is parallel to the slow ray, the elongation is positive. The direction of elongation can be observed directly, either on the crystal edges themselves or on cleavage lines. The directions of the fast and slow rays can be determined by means of the quartz wedge, as already explained, in reference to optical character.

Uniaxial minerals are usually elongated parallel to the vertical crystallographic axis c, and for this reason the sign of the optical character is usually the same as the sign of the elongation. But there are exceptions; for example, some apophyllites. In biaxial crystals the elongation direction may not be parallel to any axis of vibration, and the sign of elongation is determined by the axis nearest the direction of elongation.

COLOR OF CRYSTALS

The color of small crystals or fragments, when observed under the microscope in transmitted light, is always much paler than the color shown microscopically, in ordinary light. Very faintly colored substances, such as some amethysts, may appear absolutely colorless. Substances opaque and black to the naked eye, such as some of the ferromagnesian minerals, may be transparent, although deeply colored, when observed in their fragments under the microscope. In transmitted light under the microscope all opaque substances appear black, regardless of their color. It is consequently unsafe to draw too liberal conclusions as to colors on the basis of microscopic appearance.

With due reservations it may be said that the color shown under the microscope by substances known to be chemically pure is of some determinative value. But substances deeply enough tinted to show color in transmitted light under the microscope are comparatively scarce. When such substances are examined, however, the color should be noted.

In general, it may be said that the color of natural minerals is an ambiguous and frequently undependable guide. But here again color should be noted when present and used determinatively when conditions warrant such use. It is perhaps never safe, however, to take color alone as a determinative characteristic.

PLEOCHROISM

If white light is transmitted through any substance it will be found that somewhat less light emerges than entered. In other words, it will be found that the substance absorbed part of the light. If the amount of light absorbed is very minute, the substance is said to be transparent. If all the light is absorbed, the substance is opaque. Certain substances not only absorb some of the light, but they absorb it differentially; that is, they absorb certain wave lengths of light (certain colors) to a greater extent than other wave lengths. White light transmitted through such a substance therefore emerges with a different proportion, or even constitution of color constituents, and the substance appears to be colored. In isotropic substances the optical properties, including the absorption, are the same in every direction. Consequently, an isotropic substance is colorless, opaque, or of the same shade of the same color, no matter in what direction the light passes through it. On the other hand, doubly refracting substances have different optical properties in different directions. This may include the absorption, and if the absorption is sufficiently different in the different directions, the substance may be differently colored, depending on the direction in which the light is transmitted. Absorption of course depends partly on the thickness of the absorbing substance, and this fact should be taken into consideration when comparisons between colors are made. The phenomenon of changed colors with changed directions of transmitted light is called pleochroism, occasionally dichroism, when two colors are manifested, and trichroism when three are manifested. This property is possessed to a greater or lesser extent by a large number of doubly refracting substances, and when present has considerable determinative value.

Neither uniaxial nor biaxial crystals show pleochroism when the light is transmitted parallel to an optic axis and the microscope stage is rotated. In uniaxial crystals the maximum pleochroism is shown when the light is transmitted at right angles to the optic axis. In biaxial crystals the maximum pleochroism may lie either in the plane of the optic axes or at right angles to it. It is, therefore, necessary to know the orientation of the crystal under examination, and this can be determined as usual by means of interference figures.

The procedure is simple. Find a properly orientated particle on the microscope slide. Rotate the stage until the particle extinguishes between crossed Nicols. Remove the analyzer and observe the color. Rotate the stage 90° without replacing the analyzer and observe the color in this new position. This procedure is not, of course, obligatory. The essential elements are that the orientation be so chosen as to give maximum pleochroism and that the absorption directions be stated in relationship to the optical directions of the crystal. Pleochroism in uniaxial substances may be expressed as absorption $E>O$, as the case may be, O being the direction of vibration of the ordinary ray and E that of the extraordinary ray. Pleochroism in biaxial crystals may be expressed as, for example, absorption $(Z=Y)>X$, or X violet red, Y wine yellow, Z yellowish rose; X, Y, Z being the directions of greatest, intermediate, and least ease of

vibration, respectively. The German letters a. b and c may be substituted for X, Y, and Z, respectively.

Great refinement is not usually necessary in observation on pleochroism. Frequently the knowledge that the substance is pleochroic is sufficient, together with other data, for all practical determinative purposes. There are, however, special accessories for observing very faint pleochroism if this should be considered desirable. For such, reference should be made to the trade catalogues and to the detailed texts of petrographic methods.

For the beginner, tourmaline is perhaps one of the best substances for practice observations on pleochroic phenomena.

ORIENTATION

The term "orientation" is a general expression which includes all the relations between the optical and crystallographic directions in crystals. In a more restricted sense it refers particularly to the position of a crystal under the microscope in relation to the axis of the microscope. Angles between the principal vibration directions and the crystallographic axes are preeminently orientation data, although they also serve for extinction data. In fact, extinction angles are themselves orientation data, in that they show the angular relationships between the plane of the optic axes and some crystallographic axis or face. Complete orientation data should show the angles between every vibration direction and every crystallographic axis.

APPLICATION OF METHODS

No one of the methods previously described is in itself sufficient to identify a given substance except in rare and special circumstances. While different substances differ in individual properties, it is very frequently possible to find two distinct substances which have some particular one or more optical properties in common. For example, it can not be said that two substances having the same refractive indices are identical. There are whole series of glasses from which individual specimens can be selected having the same indices as most of the common soil minerals. Sodium nitrate and calcite are both uniaxial and negative and their interference figures closely resemble each other, but their refractive indices are markedly different. Potassium chloride, sodium chloride, and ammonium chloride are all isotropic, but they differ radically in their indices.

Different substances may thus have some particular properties in common, but still differ widely from each other in their ensemble of properties. Certain properties may be considered as general or group properties and other properties may be considered as specific. A classification is therefore possible. The following sketch of the procedure for the identification of a pure substance will illustrate the application of the methods when used in conjunction with the classificatory system generally adopted.

PURE SUBSTANCES

Mount the substance in any medium which does not dissolve or react with it and which has a known, preferably intermediate, index

of refraction. If the grains stand out very prominently under the microscope, so as to show black borders, it is best to determine by Becke lines whether the index of the grains is higher or lower than that of the oil and then to make a new mount with some other oil, with an index nearer that of the substance.

Cross the Nicols and rotate the stage of the microscope. Either the crystal under observation will remain dark during a complete rotation, or it will not. If it remains dark, raise the condenser, remove the ocular, and observe whether or not an interference figure is present. If no interference figure is visible the crystal is isometric, and one should proceed at once to the determination of the refractive index (p. 34). In Table 2 isotropic substances will be found arranged according to increasing index of refraction. If, on the other hand, the crystal alternately lights up and extinguishes during rotation, between crossed Nicols, if it remains light during rotation, or if it remains dark during rotation but gives an interference figure, it is anisotropic and belongs to some crystal system other than the isometric.

If it has not already been done, obtain an interference figure and observe whether it is a uniaxial cross or a biaxial system of hyperbolæ. If the particular crystal grain under observation does not give a suitable figure, tilt it to a new position, if practicable, or find another grain which is already properly orientated. If the figure is uniaxial, the crystal belongs to either the tetragonal or hexagonal system. If it is biaxial, the crystal is orthorhombic, monoclinic, or triclinic. Whichever the figure may be, uniaxial or biaxial, determine the optical character by means of the quartz wedge or selenite plate. This classifies the substance as uniaxial positive, uniaxial negative, biaxial positive, or biaxial negative. If the substance is uniaxial determine the ω index; if biaxial, determine the β index. Uniaxial positive substances are listed in Table 3 according to increasing value of ω. Uniaxial negative substances are listed in Table 4, likewise according to increasing value of ω. Biaxial positive substances are listed in Table 5 according to increasing value of β. Biaxial negative substances also are listed in Table 6, according to increasing value of β. Refer to the appropriate table and find the ω or β index, as the case may be, which has been determined on the given substance. If the given substance is included in the table, its name and composition will be found in the same row with the refractive index. Determine the other properties of the substance listed in the table as a confirmation of the identification. If, as may very well happen, more than one substance has about the same ω or β index in a given table, the determination of the other constants serves to distinguish these substances from each other.

IDENTIFICATION OF MINERALS IN SOILS

It is a truism, of course, that soils are the residue from the disintegration and decomposition of rocks plus organic matter. Ignoring the organic matter, a soil can therefore be expected to consist essentially of the common rock-forming minerals and their decomposition products. The mineral particles vary widely in size and are frequently much diluted and sometimes masked by the colloidal and

petrographically indeterminable decomposition products. A preliminary removal of the colloids is therefore always advisable and sometimes necessary. For quantitative work (p. 71) it is almost necessary to size the soil minerals. Both the removal of the colloids and the sizing of the minerals can be accomplished by various methods of mechanical analysis. Perhaps the simplest method is ordinary sieving. Various other methods will readily suggest themselves, for example, elutriation and centrifuging. In soil laboratories it is customary to use the equipment and methods of the current system of mechanical analysis.

Quartz is present in practically all soils and usually constitutes the major mass of the sand fractions. Its large quantity makes it a diluent for the other soil minerals. It therefore tends to distract the attention from, and increase the time of search for, other minerals occurring in comparatively small quantities, unless some means is taken to remove it, at least partly, from the range of vision. Preliminary mechanical separation of quartz from the sample is not always practicable and is seldom convenient, but it happens, as a very little experience will demonstrate, that the refractive index of quartz is exceptionally well located for soil work. If the sample is mounted in an oil with an index of refraction the same as that of the ordinary ray of quartz, 1.544, every one of the quartz grains will disappear in some one or other position of the stage, depending on the orientation of the grains. No quartz grain, regardless of the position of the stage, will stand out prominently. In this mount all the quartz is either invisible or only vaguely visible, whereas most of the other soil components stand out with a considerable degree of prominence and can therefore be readily found. Furthermore, one of the indices of refraction of the quartz has been determined by comparison with the oil. Examine some of these vaguely seen or invisible grains for interference figures and optical character. Quartz is uniaxial and positive. Complete the quartz identification either by a measurement of maximum double refraction, 0.009, which should be added to 1.544 to give the value of the undetermined index of refraction, 1.553; or make another mount in an oil of this latter index and determine the index of precisely similar particles by direct comparison. It is not necessary, but another maximum double refraction measurement on a grain of this second mount will serve as a check and will add considerably to the beginner's confidence that he is observing the same component in both the mounts if he is unfamiliar with the microscopic appearance of the soil minerals.

The first mount should now be very carefully examined for grains which have a similar vague appearance but are otherwise different from the quartz grains already determined. This examination should include the search for grains with refractive indices slightly different from those of quartz, grains which give biaxial instead of uniaxial interference figures, grains optically negative instead of positive, and grains which are isotropic instead of doubly refracting. In this examination a familiarity with the relief appearances of different probable components and with the appearance of the different orders of colors in Newton's scale, together with the lavish use of Becke-line movements, will be found invaluable.

If in this mount a grain is found which does not practically disappear in some position of the stage it is, barring the effects of surface coatings, almost certainly not quartz. A biaxial grain may rarely be quartz, but the chances are overwhelmingly against it. An optically negative grain or an isotropic grain is certainly not quartz.

It is probable that one or more vaguely visible components, differing from quartz, as indicated in the preceding paragraph, will be found. If so, determine every property which it is possible to determine in this mount. This will usually include all determinable properties except refractive indices. Estimate these by relief and Becke-line movements and determine them accurately in other mounts on grains having exactly the same composite of properties. Reference should then be made to the tables of the optical properties of minerals and the component identified by finding that mineral there listed whose properties agree with those determined.

When the region of refractive indices near that of quartz has been exhausted, find grains farther and farther removed from quartz in refractive index and proceed on each one of them as above. This procedure will lead to the identification of all determinable components found in the sample. Every mount made should be carefully scanned for components not hitherto noticed. As several mounts will probably be made during the course of the work, each one containing perhaps several hundred grains, the list of components identified can be considered as practically complete.

As an illustration of the identification of a mineral by the above procedure combined with a rigorous application of the tables, suppose that in the first mount a mineral is found with the following properties: Biaxial, optically negative, optic axial angle about 40°, cleavage microscopic and very perfect in one direction and therefore giving rise to a platy, tabletlike appearance, colorless, perceptible dispersion with $\rho > v$, the acute bisectrix emerging practically normal to the cleavage plates, double refraction on plates lying less flat than that of quartz, about 0.004, double refraction on tilted edges much greater, all indices of refraction higher than those of quartz, but, judging by relief, not much, if any higher than 1.620. This gives a composite of several properties, each of which varies from mineral to mineral. That there should be another mineral with an identical composite is of course possible, but the probability is almost vanishingly small.

Other mounts are made and two indices of refraction are measured on flat-lying plates. A third index is measured on tilted plates. Check examinations should be made of each plate on which an index is measured in order to assure one's self that it has the same identical composite of properties as determined in the first mount. Suppose the three indices measured are ± 1.594, ± 1.590, and ± 1.561. The second one, ± 1.590 is obviously β both on account of its numerical relation to the other two and from the particular orientation in which it was measured. Add ± 0.005 to this index to allow for errors of observation. This gives a minimum of 1.585 and 1.595.

In the tables, for example, those of Larsen (*10*), turn to the biaxial negative group. In the β column mark off all minerals having a β index between 1.585 and 1.595. There are some 19 of these min-

erals (*10, p. 251–253*). Six of these are immediately eliminated by the possession of distinctive characteristic colors entirely foreign to the colorlessness of the mineral under examination. One more is eliminated by lack of cleavage. Two more are eliminated by the possession of very large optic axial angles. Another is eliminated by strong dispersion of a character contrary to that of the mineral under identification. Six more are eliminated because of too low α values. This leaves three. Two of these can be eliminated by double refraction, by orientation when possible, and by the possession of two instead of one direction of cleavage. The properties of the remaining mineral, muscovite, check with those determined on the unknown, and the unknown is therefore identified.

The foregoing illustration presents an especially difficult example, both as to technic and as to the complexity of the data to be interpreted, but there are still other complications which have not been taken into consideration. One of these, and perhaps the most serious, is the natural variation of muscovite. Another is the variation of properties due to weathering. But, except in extreme cases, it is doubtful if any petrographer would experience any difficulty whatever in the identification. This is due to the fact that the properties, as written down, appear to have equal determinative value. They do not have such equal values. The highly developed cleavage, the biaxial negative character, and the emergence of the acute bisectrix almost normal to the cleavage plane are, when coupled with the relief appearance of the plates, practically enough to convince anyone familiar with minerals of the identity of this one. The observation and measurements of the other properties would be essentially confirmatory rather than determinative.

As a simpler example, suppose a mineral found with the following properties: Uniaxial, optically negative, extremely high double refraction (0.172), $\omega = 1.658$, and occurring as rhomblike forms. Adding ± 0.005 as a safety factor to the known index gives 1.653 and 1.663. Reference to the uniaxial negative group of tables shows only four minerals with an ordinary ray index between these limits. Three of these have double refractions entirely too low. The remaining one, calcite, has properties which check with those determined.

After each identification the worker should, at least until he is intimately familiar with the appearance of the common minerals, make up a mount from a known sample and compare it in more or less detail with the just identified "unknown." It will be found that most minerals have outstanding characteristics which materially reduce the labor and add to the certainty of identification. Among these characteristics are the twinning of the feldspars, the high double refraction of the calcite-dolomite-siderite series, the cleavage of the micas, the high refraction of rutile, the low refraction of fluorite, and the color, within limits, of ferromagnesian silicates such as augite and hornblende. It is true that the tables contain all these facts, but they do not, and probably can not, give them proper emphasis without opening up possibilities of misinterpretation. To those familiar with the minerals there is no need of any such emphasis, and no one unfamiliar with them should attempt their identification in soils or rocks.

The procedure for the identification of minerals in soils as written above is in no sense obligatory. It is intended primarily as a guide, reliable though possibly cumbersome, for beginners. It, therefore, very probably goes into details altogether unnecessary for those previously experienced in some other application of petrographic methods. For the encouragement of beginners it should be stated that, with the development of manipulative skill and barring the necessity for time-consuming search, any ordinary mineral should be identified in a soil or elsewhere in a maximum of not more than 15 minutes, probably much less. The beginner should be advised against a too-rigorous application and slavish following of the tables. At the best the tables are guides, and in no sense are they systems of ultimate pigeonholes, in which every substance fits snugly in its ordered place without possibility of erratic arrangement. In the main, minerals, in common with most other natural objects, are variables, and there is perhaps no substitute for an intimate first-hand knowledge of them.

There are special problems of identification of soil minerals for which no definite procedure can be outlined beforehand. The identification of weathered and decomposed minerals gives rise to perhaps the larger group of these problems. A decomposed mineral is, from the very fact that it is decomposed, different from what it was before decomposition. The determination of its original nature therefore literally means the determination of what it was before it was changed into what it is. If decomposition has gone too far the problem is of course insoluble. For example, there are no means known at present by which the parent species of the clay minerals of soils can be determined. One can conjecture, and in certain cases there might be a basis in fact and in reason for the conjectures. For instance, if the parent rock is a mica schist consisting essentially of quartz and micas, and if there is no probability of the clay having been brought in from outside sources, it is reasonable to believe that the clay minerals are the decomposition products of the micas. This reasoning, however, is in no sense a determination. Such absurdly extreme examples could be multiplied.

The usual type of cases is that in which the original mineral has been partly but not wholly altered and has certain of its primal characteristics remaining. Biotite furnishes a fair example. Under the influence of the weathering agencies its iron is oxidized, and there is a tendency toward the extraction of the bases. Optically the color changes, the interference figure becomes blurred, and its refractive indices may change slightly. On the other hand, its highly characteristic cleavage and optical character remain. In the early stages of decomposition the changes are so slight as to be negligible, but they become progressively greater and greater. Suppose they have progressed to the point where the observable and measurable properties do not yield sufficient data for identification and where the general appearance is decidedly that of decomposed material. How is one to know that this is decomposed biotite? Speaking in terms of definitive, unquestionable knowledge, the answer is, of course, that one can not know. But for practical purposes and within the limitations of reasoning implied by such purposes, the means of knowing are comparatively simple. In the first place, the substance has

some of the properties and characteristics of biotite. These are indicative. If, in the second place, the observer's experience has included the examination of biotites in various and numerous stages of decomposition, he will recognize that the material under examination shows not only the residual properties of decomposed biotite but also the very changes and alterations common to weathered biotite. He will, therefore, be able to approximately classify his material at some place in a known series. This is not absolute identification, but it has a high degree of probability.

In any work of this kind the question is likely to arise as to just how far a given mineral can be altered and still be called by its original name. Since alteration is a fairly continuous process, at least over a considerable part of its range, any such line of demarcation between, say, biotite and nonbiotite, would have to be arbitrary and would present almost insuperable difficulties in its location. The solution of the question in any given case must, for the time being, be left to the common sense of the individual worker.

Another type of identification is that presented by inclusions of one substance in grains of another. These inclusions may be gaseous, liquid, or solid. Quartz and volcanic materials are especially apt to carry them, although they may very well occur in other soil minerals. Gaseous and liquid inclusions can be readily distinguished from each other and from solid inclusions by the comparative width of their dark borders. These dark borders are total-reflection phenomena depending on the relative refractive indices of the inclusion and the including material. As the refractive indices of gases and liquids are usually quite different both from each other and from solids, the dark borders are wide and prominent in the case of gases in solids, present to some extent but not so pronounced in the case of liquids in solids, and absent or imperceptible in the case of solids in solids. Occasionally liquid inclusions carrying a bubble of gas are found.

Generally speaking, residual material is much more apt to carry inclusions than is distantly transported material. The reason for this is apparently that the inclusions cause strain in their carriers and, therefore, render them more subject to comminutive forces than are the grains free from inclusions. The result, of course, is that, in the main, distantly transported material is relatively free of inclusions.

The solid inclusions are commonly rutile, apatite, calcite, and limonite. The difficulty in identifying the inclusions is sometimes due mainly to their small size. But the more usual difficulty is due to the impracticability of obtaining complete optical data. The inclusions are in contact with their containing minerals and not with the mounting medium. Refractive indices must, therefore, be estimated by relief and are consequently subject to all the errors of this method. The other optical properties are equally difficult to determine. On the other hand the inclusions, when crystalline, usually occur in well-developed characteristic forms. Rutile, for instance, occurs as long slender needles which can scarcely be mistaken for any other mineral. The procedure, then, is to mount the containing minerals in an oil in which they disappear, thus revealing the inclusions. Obtain all the optical data possible on the inclusions, and pay particular attention to the crystallographic form and habit. The

combined optical and crystallographic data are frequently sufficient to lead to a reasonable, though not always conclusive, identification. Fortunately, the identification of inclusions becomes of importance only in reference to very special problems.

Occasionally it is necessary or desirable to know something of the origin of the soil quartz. Primary quartz, that is quartz which originated by crystallization from a magma, may carry inclusions of those minerals which themselves crystallized from the magma. Rutile needles are the commonest and perhaps the most characteristic of this type of inclusion. On the other hand, secondary quartz, that is, quartz which originated by crystallization from water solutions, may carry inclusions of those minerals which are themselves of a secondary character. Limonite and calcite are characteristic of this type of inclusions. It is possible, of course, for secondary quartz to carry inclusions of primary minerals, but it is scarcely thinkable that primary quartz should carry inclusions of secondary minerals. This, of course, is on the assumption that one has made careful observations to convince himself that the inclusions are actually such and are not infiltrations through cracks and crevices. It follows, of course, that quartz containing secondary minerals as inclusions is itself of secondary origin; quartz containing no inclusions may be, so far as we can tell, of either primary or secondary origin, and quartz containing primary minerals as inclusions is probably itself of primary origin. In certain characteristic cases this probability becomes perhaps more than a practical certainty. A quantitative estimation of the percentage of quartz-carrying secondary inclusions will give a minimum value for the quantity of secondary quartz in the sample.

By way of summarization it may be said that with clean sand fractions of such youthful soils as the Durham and such naturally sorted materials as some of the coastal-plain soils, the petrographic identification of the constituent minerals attains a degree of certainty somewhat greater than that reached in the identification of consituents of rock sections. The reason for this is that, with the sands, as many mounts as needed may be made and the orientation of individual grains may be altered, thus making possible the actual measurement of the optical properties, notably the refractive indices, instead of approximately estimating them, as is frequently necessary with rock sections. The degree of certainty is perhaps as great as is attainable by petrographic methods alone, and when these methods are used in conjunction with chemical analysis the identifications can be considered as practically absolute. The identification of minerals in the silt fractions of soils, although still comparing favorably with identifications of similar-sized materials in rock sections, does not always give as clear-cut and comprehensive results as are obtained on the larger-sized sand particles. Ordinarily there is no reason whatever for doubting an identification of a silt particle, but the petrographer has a tendency to feel that he could get better and clearer results if the particles were larger. Particles of the clay fractions of soils can not, of course, be identified at all petrographically, and recourse must be had to X-ray methods. In the sands and silts the identity of decomposed minerals can be established with varying degrees of assurance ranging

from practical certainty to no certainty at all, depending on the extent of decomposition. The petrographer has to exercise his common sense in deciding just how far he can carry the identification.

PERCENTAGE ESTIMATION OF CONSTITUENTS IN A MIXTURE (MECHANICAL ANALYSIS)

In addition to determining the minerals present in soils, it is frequently of great importance to determine their relative quantities. In such instances there are in general three types of preparation, the constituents of which the microscopist may be called on to estimate. In soils laboratories these mixtures may be either firmly consolidated as rocks, or, on the other hand, may be in the form of loose materials. Of these, the simplest to estimate is the rock-section type of mount, in which all the particles can be assumed to have the same thickness and are usually in contact with each other without vacant spaces over the whole field of the microscope. A second, more difficult type of preparation, is that presented by ordinary mounts of previously sized materials, such as separates from mechanical soil analyses. Here the thickness of the particles can not always be assumed as uniform, and the amount of vacant space in any given field of view is frequently large. The third type of preparation and the most difficult of all is that in which there is no preliminary sizing whatever and in which the amount of vacant spaces is large. This type is presented by mounts of untreated soils, crushed crystal mixtures, crystal mixtures obtained by direct evaporation on the slide, and a multitude of similar materials from various sources. All the types are further slightly complicated by occasional overlapping of particles and by the presence of inclusions of one substance in another. The second and third types are sometimes seriously complicated by coatings of one or more substances on grains. The third type is frequently complicated by aggregates, the character of which is indeterminate.

No matter which type of preparation one is working on, the first task is to identify, so far as possible, every substance occurring in the mixture. With coarse-grained rocks and clean sands this identification is usually complete and easy. With other mixtures, the identification of certain of the constituents is frequently difficult, and, in the case of aggregates, deeply coated grains, substances whose optics are unknown, substances with abnormal optics, and extremely fine-grained substances, the identification may be impossible or practically so. With such mixtures there are thus three classes of constituents: (1) known constituents to be estimated individually; (2) a class of doubtful substances to be subgrouped and estimated as probably so-and-so, or as having such-and-such properties; and (3) a class of unknowns to be lumped together and estimated as such. Aggregates can sometimes be broken up into their constituents by simple crushing or by treatment with acids to remove cementing material. Coated grains can frequently be cleaned by treatment with hydrochloric or oxalic acids, and extremely fine-grained materials can often be improved by allowing the crystals an opportunity to grow.

By these and similar means which will readily suggest themselves to a chemist, doubtful and unknown substances may be rendered

identifiable. The qualitative identification of the constituents of the mixture, which are usually comparatively few, almost always brings to the attention some characteristics of the different constituents which serve to distinguish any one of them, practically at a glance, from all the other constituents present. For example, one of the constituents may be colored, whereas the other constituents are colorless or differently colored, as is the case of hornblende admixed with quartz, orthoclase, or perhaps micas. One of the constituents may have a very high double refraction, whereas all the other constituents have comparatively low double refractions, as would be the case of calcite or dolomite in the mixture just cited. If this same mixture were mounted in an oil with an index of refraction very near that of quartz, the orthoclase and colorless mica could be immediately distinguished from the quartz by their reliefs and from each other by the opposite movements of the Becke lines on slightly raising the tube of the microscope. If a mixture of sodium and potassium chloride is mounted in an oil with a refractive index between the indices of the two substances, the movement of the Becke lines would again immediately distinguish one from the other. If ammonium chloride is added to the mixture its relief in the same mount as above would serve to identify it in this mixture.

Thus, knowing what substances are present and having a means for the immediate recognition of each of them, the worker can proceed with his quantitative work unhampered and uninterrupted by the necessity of a long process of qualitative identification. Furthermore, the preliminary qualitative identification gives one a very definite idea of the best mount for the quantitative work; for instance, it shows the one best oil in which to mount the sodium and potassium chloride mixture mentioned above, that is, an oil with a refractive index between those of the two constituents. It occasionally happens, rarely, however, that two constituents of a mixture have properties so nearly alike that immediate distinction during the quantitative process is difficult. What to do in such a case depends not only on the characteristics of the two similar substances but also on the characteristics of the other substances in the mixture. It may even become necessary to determine the combined quantity of the two substances in one type of mount and then determine their mutual ratio in an entirely different type of mount.

To determine the percentage composition of a rock section, calculate the total area of the microscope field for the particular lens combination used by means of the formula

$$A = \pi r^2$$

where A is the area, π is 3.1416, and r is the radius of the field expressed as linear checkerwork eyepiece micrometer divisions. If any vacant places are present, determine their total area by micrometer count and subtract the result from the field area just calculated. This gives the net area covered by the substances to be estimated. Determine by micrometer count the areas of each substance in the field. As a check on the counting, the sum of the areas of the substances plus the areas of the vacant spaces, if any, should equal, or nearly equal, the total calculated area of the field. Any large discrepancy indicates an error in counting, and the work should be

repeated. Some systematic procedure in counting, for instance, by quadrants and left to right by rows or columns on the micrometer, is practically a necessity. It relieves eyestrain, lessens the tax on the attention, and often avoids the total loss of count due to interruption.

Since the thickness of the rock section can be assumed as uniform, the volumes of the constituents vary with their areas. The area of any one substance, therefore, divided by the net area of the field and multiplied by 100 gives the percentage by volume of that substance; that is,

$$\text{Per cent by volume} = \frac{\text{Area of substance}}{\text{Net area of field}} \times 100.$$

In this way the percentage by volume of each constituent can be determined, and the total should, of course, equal nearly 100. But it is not often that the percentage by volume is wanted, as practically always the percentage by weight is desired. This can be obtained from the volume percentage by multiplying the volume percentage of each constituent by the specific gravity of the constituent, summing up the figures so obtained, and taking the ratio between the figure for the individual constituent and that of the sum. A more direct method is to multiply the area of each constituent by the specific gravity of the constituent, sum up the figures so obtained, use the figure for an individual constituent as the numerator, the sum as the denominator, reduce this fraction to a decimal, and multiply by 100. This gives the percentage by weight of the constituent considered.

The sources of error are variations in the thickness of the section, inaccuracies from whatever cause in the counting, the presence of unestimated or only approximately estimated inclusions of other substances, and inaccuracies in the figures taken for the specific gravities. These latter vary considerably in certain minerals, and usually there is no practicable way of knowing precisely what figure to select.

In spite of these sources of error, however, the method is remarkably exact when applied to a single field of the microscope. But to make it applicable to the entire work it is necessary to resort to statistical methods. A number of fields should be counted and the results averaged. If the rock is very uniform, a very few fields are sufficient. If, on the other hand, the rock is very variable, it is necessary to increase the number of fields. Right here there is room for the exercise of a considerable amount of judgment. Theoretically a number of fields should be taken so that the addition of any other probable field will not seriously alter the average figures already obtained. Throughout all the work the areas themselves need not be determined by actual count. Any method, for instance the statistical linear method given in the discussion of area measurements may be used.

The procedure for the percentage determination of loose but sized material may be substantially the same as that given for rock sections. Usually, however, the vacant area on the slide exceeds that of the constituents. For this reason it is better to obtain the total area covered by the constituents, either by actual count or by

summation of the counts of the individual constituents, rather than by counting the areas of the vacant spaces and subtracting the total from the field area. The final results, however, are not of the same order of accuracy as those obtained for rock sections. All the sources of error in rock sections are still present and that one due to variations in thickness is vastly increased. For example, rounded quartz grains and flat flakes of mica of the same minor diameter would be held by the same screen in the sizing operation. But their thickness on the slide would be vastly different, and consequently the calculation of volumes or weights on the assumption of uniform thickness might be very seriously in error. Such error can be partly eliminated by measuring the thickness of each grain and calculating the volume by multiplying this thickness by the area of the grain. This procedure does not entirely remove the inaccuracy, since the grains are almost always rounded instead of rectangular, but it yields results sufficiently approximative for most purposes. If none of the constituents shows a thickness of uniformly extreme variation from the average thickness of all the particles present, it is safe to assume that the volumes vary approximately the same as the areas. The determination of both the area and thickness of each individual particle is likely to be a long and tedious job. It can frequently be shortened by multiplying the total area of the thin substance by a factor whose value can be determined from the relationship between the average thickness of the thin substance and that of the other substances in the mixture. In most cases of carefully sized materials, such a factor can usually be determined from a comparatively few thickness measurements.

It is seldom that all the detailed work indicated in the preceding paragraph is justified by the requirements of the problem; in fact, it is very doubtful whether the additional degree of accuracy obtained is ever sufficient to justify the time and labor expended. This can be realized readily when it is recalled that the percentage composition of a single field bears only a statistical relation to the true composition of the sample. The preceding paragraph has been written more with the idea of bringing out the principles involved than with any idea as to the actual application of the details except in extremely rare and unusual circumstances.

The method usually employed for the analysis of carefully sized materials is simply the direct count of the number of particles of each constituent. The composition by volume then is

$$\text{Per cent by volume} = \frac{\text{Number of particles of one constituent}}{\text{Total number particles counted}} \times 100.$$

The percentage by weight can be readily calculated as given in the discussion of rock sections. This method is based on the assumption, usually well founded, that each substance in the mixture has the same average particle volume. Mica is the most common exception. The number of mica or similar particles should be multiplied by a factor which can be determined by a comparison of the volume figures obtained by area and thickness measurements for a few of the mica and nonmica particles. If the number of mica particles is insignificant, as is the case in certain soils, it is scarcely worth while to make this correction. On the other hand, highly micaceous soils will yield

results wide of the truth if the factor is not applied. It should be remembered that a comparatively small quantity by weight of thin mica flakes can make an altogether disproportionate showing when scattered throughout a soil.

If the material is unsized and if the particle sizes vary widely, results of even a fair degree of accuracy are probably not attainable by any method other than that involving the volume determination of each individual particle by means of areal and thickness measurements. If colloidal material is present in quantity too great to be neglected, as in most soils, the quantitative determination of the percentage composition is practically a microscopic impossibility unless the colloids can be estimated by some other than microscopic means and allowed for in the calculations of the noncolloidal constituents. It may be said, in general, that the quantitative microscopic analysis of such materials as those under discussion should be undertaken only under the most exceptional circumstances.

Nevertheless, the microscopist is continually being called on to give some sort of estimate of the quantity of one or more constituents in just such materials. Rough approximations can be arrived at as follows: Determine the percentage of the constituent by rapid areal measurements. Determine by inspection, supplemented if necessary by a few thickness measurements, whether the average particle thickness of the constituent is near, less than, or greater than the average particle thickness of the mixture. If near, the percentage can be reported as about so-and-so; if less than, it can be reported as not greater than so-and-so; and if greater than, it can be reported as not less than so-and-so. Ordinarily, this rough sort of approximation is sufficient for the purpose. It at least gives a fairly reliable idea of the maximum or minimum quantity probably present.

It scarcely need be said that in all quantitative work on loose materials the grains should be as free as possible from coatings and adhesions of foreign substances, as it is practically impossible to make any estimation of the total volume of such substances. Coatings of opaque materials, such as iron hydroxide, may lead to an entirely wrong identification of the grain. Calcium carbonate is a particularly bothersome coating. Its high double refraction and relief in ordinary mounts, even when occurring only as a thin veneer on other substances, may lead to a very large overestimate of the quantity present. Alkali salts have a strong tendency to occur as coatings on the other soil grains. In general it is best, where practicable, to determine the quantity of colloids, including organic matter, calcium carbonate, and water-soluble salts by chemical means and to determine the other constituents microscopically in the residues.

Mineralogical analyses of soils (*11*) show that the following minerals may ordinarily be expected to occur in soils, though not all of them in any one soil: Quartz and other forms of silica such as chalcedony as the major component; most of the feldspars as orthoclase, microcline, albite, oligoclase, andesine, and labradorite; muscovite and biotite; chlorite; glauconite; epidote; hornblende and glaucophane; pyroxene, especially augite; magnetite, hematite, and limonite; apatite; and calcite and dolomite. Almost any other mineral may occur occasionally under special circumstances.

DIFFERENTIATION OF SOIL COLLOIDS FROM SOIL CRYSTALLINE MATERIAL

It is well recognized that in addition to the definite crystalline material in soils there are always present quantities of material varying from a small percentage up to sometimes as high as 80 per cent of material which can not be identified by petrographic methods. This material is of two general types—inorganic material, presumably formed by the decomposition of minerals, and organic matter, which comprises, for the most part, the residual products derived from animals and plants. Most of this material is extremely finely divided. Soil scientists are accustomed to describe it in terms of particle size after dispersion in water alone or in water with the addition of dispersing agents. After dispersion this material consists of very small particles ranging from 5μ downward. Soil scientists usually designate this extremely fine material as clay, regardless of its chemical composition. It follows, therefore, that the soil clay is not necessarily chemically identical with the amorphous mineral known as kaolin. Many soil scientists divide this portion of the soil into two parts, one of which is known as soil colloid because it possesses, to a great degree, those properties which characterize the group of substances of diverse origin which are so known and which possess the properties of moisture absorption, swelling with water or other liquids, and the ability to adsorb ions of various sorts. Where the dividing line should be drawn between the coarser noncrystalline material and the supposedly truly colloidal part of the soil has not found general agreement. To some scientists, any material which, in the dispersed condition has a maximum apparent diameter of 2μ or less is colloidal; others wish to make the upper limit 1μ, and some continue to regard as colloid only that material having a maximum apparent diameter of 0.1μ.

It is not the present purpose to attempt a discussion of this problem for the reason that, to the soil petrographer, the only differentiation that is possible is between those particles of the soil which have definite mineralogical and petrographical characteristics and those which have not these characteristics. To him, then, all which is not definitely crystalline under the microscope is more or less definitely colloidal in character. This distinction may be kept in mind in spite of the fact that X-ray studies (*6*, *9*) have shown that many substances with marked colloidal properties gave definite diffraction patterns and are therefore crystalline, and in spite of the fact that even the typical colloid from which the group name is derived, gelatine, in the dry condition, gives a perfectly defined interference figure in polarized light. Glass also, which is generally considered as a true colloid, often shows the phenomenon of double refraction. It would appear, therefore, to the student of petrography of soils that his province is limited to differentiating between identifiable materials on the one hand and those not definitely determinable on the other; and, further, to gaining such information as may be useful concerning the unidentifiable fraction. It may be remarked that the lack of agreement above mentioned concerning even the size limits of those particles which shall be called colloidal accounts for the divergence between the quantities of colloid as ascertained by microscopic examination and those obtained for the same soils by other methods. It is suggested, therefore, when studies are made of this

unidentifiable or incompletely identifiable fraction of the soil that the results should be ascribed to unknown substances having such-and-such properties and characteristics, probably (or possibly) so-and-so. Or, when the data obtainable do not justify even a guess as to their nature, simply as unknown substances having such-and-such properties and characteristics.

This manner of reporting results automatically limits the term colloid to that portion of the sample consisting of particles of unknown substances which are within or near generally accepted colloidal dimensions. It will be seen that in such case the term will apply equally to organic and inorganic material. Nevertheless, information of considerable importance concerning this fine material present in the soil may be obtained by the use of the petrographic microscope.

In dry soils, such as are used for ordinary or petrographic study, the colloids occur as aggregate masses, either free or as coatings on other soil materials. The one characteristic that all seem to have in common is the aggregated structure. This can frequently be recognized by ordinary transmitted light. The masses are seen to be not uniform continuous material but conglomerations of multitudinous and extremely fine particles. This is particularly noticeable around the edges of the mass. The fracture is not along cleavage lines as in certain minerals. To the naked eye it generally appears conchoidal, but under the microscope the conchoidal surfaces are seen to be totally lacking in the smoothness and mirrorlike qualities of the fracture surfaces of such materials as glass or quartz. On the contrary, the fracture surface of the colloid aggregate is usually an especially favorable place to observe the very fine particles. Examination in reflected light shows the same thing and sometimes to better advantage in the case of subtranslucent to opaque aggregates. Reflected light from a vertical illuminator (pp. 25, 82) occasionally brings out an aggregate structure which would not be easily visible with ordinary reflected daylight. Best of all, examination with a dark-field illumination practically always renders the structure distinct and unmistakable. During the course of the microscopic examination with ordinary light the color of the aggregates, both in transmitted and reflected light, should be noted as well as their degree of transparency or opacity.

Under the petrographic microscope, between crossed Nicols, the aggregates of soil colloids may or may not be doubly refracting. Those showing some degree of double refraction are perhaps more common than those showing none. Absence of double refraction, isotropy, seems usually associated with high iron content.

The appearance of the doubly refracting aggregates between crossed Nicols is variable. Sometimes it is that usually spoken of as aggregate polarization—that is, the aggregate appears speckled with small light and dark areas which alternately extinguish and light up as the stage is rotated. More often, however, the polarization is wavy—that is, the aggregate does not extinguish all over at the same time, but progressively from part to part as the stage is rotated, the band of extinction being usually vague as to borders, comparatively narrow, and always followed by a band of light. Occasionally the appearance simulates that of ordinary normal crystals.

Interference figures are usually easily obtained from the doubly refracting aggregates, but they are not universally obtainable. These figures at best are fairly clear and distinct, but never nearly so good as those given by clean well-crystallized calcite or quartz, for example. At the worst, the figures are barely discernible. Usually they are considerably blurred and unsatisfactory. The optic angle, as estimated from the interference figures, varies from sensibly zero up to values where the foci of the hyperbolæ are outside the field of the microscope. There are therefore aggregates which could be classed as uniaxial or biaxial, as the case may be. In any one sample the optic angles of various aggregates may vary considerably. The gypsum plate shows that certain aggregates are optically positive and others optically negative. No correlation between any of these properties and chemical composition is known.

The refractive indices of aggregates of soil colloids usually vary from about 1.56 to 1.62. There are aggregates, however, especially in lateritic soils, with very much higher indices. The refractive indices seem to vary with the iron content.

The preceding description of aggregates of soil colloids brings out the fact that they possess numerous properties in common with crystalline material. Their one outstanding and distinctive characteristic is the aggregate structure. Fortunately, however, there is only one common soil constituent with which they may be confused. This is highly decomposed mica, and there are real grounds for the tentative belief that highly decomposed mica should be classified as a colloid. But, aside from this possibility of misidentification, a very little experience should enable one to readily differentiate soil colloidal aggregates from any other substance likely to be found in soils. The general problem of determining by microscopic means alone whether any given substance is colloidal or crystalline is perhaps insoluble with our present knowledge. X-ray methods offer perhaps the best solution of the problem (*6*, *9*).

SOIL ORGANIC MATTER AND RESIDUE OF ORGANISMS

The organic matter of soils consists predominantly of plant residues in various stages of decay. There is also present, of course, organic matter from animal and other sources, but the quantity is comparatively small, and the identity of the material is seldom determinable. Bacteria, nematodes, earthworms, fertilizer applications, etc., furnish their quotas. No matter what the source, however, soils are devoid of crystalline organic matter, detectable microscopically, without a considerable amount of preliminary extraction and purification. Petrographic methods are, therefore, inapplicable to the organic matter of untreated soils. But something can be done by direct microscopic observation. Cell structure is a characteristic of practically all vegetable and animal tissues and is not found elsewhere in nature except in such rare and unusual substances as petrified wood. The existence in a soil, therefore, of material showing cell structure is practically always sufficient evidence of its organic nature. Detailed identifications as to genus and species are problems for those specializing in the subjects concerned, for instance botanists and bacteriologists.

Charcoal, bituminous coal, and anthracite present slightly different problems. All three are opaque and have no optical properties of determinative value. Their streaks, obtained by rubbing the materials on white paper, are indicative but not conclusively so. Occasionally it is possible to observe cell structure in charcoal by reflected light. If particles sufficiently large can be isolated from the soil, their combustibility can be tested and their odor and behavior on burning ascertained. Aside from the application of such miscellaneous tests as these, there is no way of identifying any of these three substances.

Investigations on the organic matter of soils, involving extensive extraction and purification operations, frequently yield organic products of a crystalline nature. There is usually a considerable amount of chemical information available, and the petrographer is called in largely in a confirmatory capacity. The procedure is simply a comparison of the optics and other characteristics of the given substance with those of the substance or substances which the chemical information indicates as probable or possible. On account of the meagerness of the published data on the optics of organic compounds, it is commonly necessary, and always safer and more satisfying, to make this comparison by a direct examination of all the substances involved.

There are certain inorganic residues of organisms, which sometimes assume importance in soils. These may be generally comprised under the denominations of shell fragments, diatoms, and sponge spicules. Shell fragments are important mainly because of the calcium carbonate of which they are composed and to a less extent because of the light their presence sometimes throws on the previous history of the soil. They can be immediately identified by their general appearance and can be readily located in mounts by their extremely high double refraction between crossed Nicols. The presence of diatoms throws light on a soil's previous history. They can be identified as diatoms by general appearance, but specific identification as species is beyond the field of petrography. Sponge spicules not only give information as to the history of the soils in which they occur but, in at least one case, have assumed practical importance on account of the irritating effect they had on the feet of mules used in plowing the fields. They are readily identified by their long, narrow, slightly curved, hollow, sometimes spined, and sharply pointed forms. Specialists easily distinguish between fresh-water and salt-water species and thus add to the known history of the soil.

SHAPE OF PARTICLES

The examination of soil particles as to shape sometimes assumes importance, especially in reference to the degree of rounding and the conclusions as to weathering and transport which can be drawn therefrom. In this sort of examination it is essential that the outside and not the inside of the particles be clearly visible. For identification purposes, as has been seen, the better the mount the nearer are the refractive indices of the particle and the oil. This greatly accentuates visibility of the interior and subordinates that of the exterior of the particle. In the perfect case the outlines of the

particle are invisible. Obviously, a directly contrary effect is desired when the exterior characteristics are to be observed. This is readily obtained by mounting the particles in a medium, the refractive index of which is markedly different from those of the particles. This type of mount subordinates the interior and accentuates the exterior characteristics of the particles. For soil particles, water or air, preferably the former, is a fairly satisfactory mounting medium. The water, however, when used alone, evaporates rather rapidly and in so doing pulls the particles so close together as to hide many of the individual edges. The addition of more water does not necessarily correct this packing, and seriously alters the positions of the grains. These inconveniences can be largely eliminated by using a minimum amount of water and carefully forming a rim of oil around and slightly under the edges of the cover glass. This type of mount is by no means permanent, but if properly made will delay evaporation sufficiently to give ample time for the examination. The examination itself is simply direct observation as to whether the particles are in general smoothly rounded, smoothly elliptical, or sharply angular with rounded edges. A quantitative expression of the degree of rounding can be obtained by statistical calculations from a number of measurements of maximum and minimum horizontal diameters and, if desirable, vertical diameters.

A certain amount of judgment is necessary both in obtaining and in interpreting the data. Extremely resistant minerals, such as zircon, are apt to retain beautifully distinct crystallographic forms long after the other minerals of the soil have become round. In fact, sharply angular crystals of zircon are common components of certain beach sands. The outline form of mica plates is particularly difficult to interpret, owing to the unusual properties of this mineral, its softness, capacity to bend, elasticity, cleavage, and ease of flotation. Fibrous and needle-shaped minerals often retain these forms to some extent, at least, regardless of the amount of transport and weathering. Feldspars, on account of their cleavage and twining, are liable to show an angularity greater than would normally be expected in certain distantly transported soil. On the other hand, they seem to show more rounding than would normally be expected in highly weathered sedentary soils. This is probably explained by their susceptibility to chemical weathering and the absence of breakage in such soils. Quartz particles have no properties which would throw serious doubts on the interpretation of their angularity or roundness, as the case may be, and are usually the most abundant components above silt size. For these reasons quartz is perhaps the safest of all soil minerals on which to base conclusions.

As the preceding paragraph shows, the comparison of the two soils as to particle shape is susceptible to various complications which can not always be easily solved. But in spite of this, it is a fact that there are soils in which the particles are in general distinctly rounded, others in which they are just as distinctly angular, and still others in which they are of a shape intermediate between the two extremes. These three groups are easily distinguishable from one another. But close distinctions between members of the same group, especially of the group consisting of intermediately shaped particles, are apt to be uncertain and unsatisfactory.

RESIDUES FROM THE EVAPORATION OF SOIL SOLUTIONS

In the main, residues left on the evaporation of soil solutions are fairly well crystallized. They consist essentially of the chlorides, sulphates, carbonates, and sometimes nitrates of the alkali and alkaline-earth metals. Other substances may, of course, be present and sometimes in important quantities, for instance, borax. Soils from humid areas yield small total quantities of residues, whereas soils from arid alkali areas may yield excessively large total quantities. In general, it may be said that gypsum and calcite are the commonest constituents in residues from humid soils, and that these, plus a whole assortment of the chlorides, sulphates, and carbonates, are common in the residues from alkali soils (*1*).

There are only two sources of difficulty in the identification of these salts. If the evaporation has been too rapid, the crystals are apt to be extremely small and closely interwoven or mutually enmeshed. The result is a heterogeneous mass of small, closely aggregated crystals, the individual components of which are practically indeterminable. Evaporation at room temperature, although slow, yields a much more manageable product than does more rapid evaporation at higher temperatures, and it probably saves time in the long run. Cases have arisen in which partial resolution and recrystallization were necessary.

A second source of difficulty in identification arises from the presence of colloidal coatings, inorganic, organic, or both, on the crystals. Filtration of the original solution through Pasteur-Chamberland filter tubes does much to prevent these coatings. If the filtered solution is boiled to coagulate the colloids, but not sufficiently to reduce the volume to the point where crystallization begins, and then refiltered through Pasteur-Chamberland filters, an additional quantity of colloid is removed and the chances of coatings still further reduced. This is usually sufficiently efficacious so far as inorganic colloids are concerned. But sometimes the solution contains organic materials which persist in spite of the treatment and which, if not removed, form the most bothersome sort of coatings. Evaporation, treatment with absolute alcohol or ether, resolution, and recrystallization will usually remove the organic matter and yields salts sufficiently clean for identification. If the volumes are small the cleaning process outlined above is not onerous, but large volumes mean a long and tedious task.

The procedure for the petrographic identification of the salts, once they are obtained in an identifiable condition, is exactly similar to that for the identification of soil minerals. As with certain fertilizer materals, however, there is the possibility of the presence of numerous double salts, and care is necessary in order to avoid missing some of them.

Where complete data are not desired, far less elaborate procedures can be devised. About the simplest procedure is to evaporate a few drops of the solution, concentrated somewhat if necessary, directly on a microscope slide, and to examine the crystals either as they form or after drying. Gypsum, on account of its low solubility as compared to the alkali salts, is usually one of the first substances to crystallize and appears in well-formed characteristically shaped crys-

tals, which are readily recognizable. Carbonates and nitrates can be recognized by their high double refraction and can be further identified by other optical determinations. Refractive-index measurements are necessary to distinguish between sodium and potassium chlorides. Sulphates other than gypsum usually require fairly complete data for certain identification.

VERTICAL ILLUMINATION

The vertical illuminator is almost universally used in the examination of metals and ore minerals (*15*). In a soils laboratory it can be used to advantage in the examination of opaque materials and of surfaces; in fact, wherever reflected light is normally used. It improves the illumination, enables the worker to see into holes and cavities where slanting side light would not reach, and, in conjunction with Nicol prisms, furnishes a means for determining the isotropy or anisotropy of opaque substances, the latter being something which can not be done at all with the ordinary petrographic equipment. For this purpose, a Nicol is placed in the path of the horizontal beam of light and the analyzer Nicol is inserted in the tube of the microscope. The first Nicol is rotated until it is in the crossed position with reference to the second Nicol. Under these conditions an isotropic substance will remain dark during a complete rotation of the stage, whereas an anisotropic substance will alternately darken and lighten as the stage is revolved. Substances which remain dark are either amorphous or isometric, and substances which alternately lighten and darken are crystalline and belong to one of the systems of crystallization other than the isometric. In determinative work this information enables one to eliminate a large group of substances.

PARTICLE SURFACES

The mounting for the examination of the surfaces of soil particles is the same as that for the observation of particle shape. Highly weathered surfaces, especially of the feldspars, usually have a pitted and corroded appearance. Fresh crystal faces and cleavage surfaces, on the contrary, are smooth and sometimes mirrorlike. Fracture surfaces are jagged or conchoidal, according to the nature of the substance. Fused surfaces can usually be recognized by their smooth globular form. Any surface may carry coatings or adhesions of foreign materials, especially of colloids such as iron hydroxide, clay materials, and organic matter.

Whether transmitted or reflected light should be used depends on a number of circumstances, such as the nature and thickness of coatings, size of particles, and their opacity or transparency. In general, it is best to try both. It is even sometimes advisable to change entirely the system of mounting and to search for impurities in the same mounts that are used for identification purposes. Whether these impurities are inclusions, surface adhesions, or both can then be determined by examination of the surfaces themselves.

Ordinarily the detailed examination of the surfaces of soil particles does not furnish any particularly important information which could not be obtained as well and sometimes perhaps better otherwise. Special occasions arise, however, where a large part of the interest

centers in the surfaces. For example, in the study of methods for the dispersion of colloids, it is essential to know something as to the extent to which colloidal coatings have been removed from the soil particles.

Mixed crystals obtained from various sources, the evaporation of soil and similar solutions, and phase-rule studies, frequently show crystals of one substance carrying partial coatings of crystals of the second substance. If an examination of the materials shows no instance of a contrary relation between the two substances it is reasonable to assume that the second substance crystallized subsequent to the first. An indication is thereby obtained as to the relative solubilities of the two substances in the given solution.

SOIL STRUCTURE

Microscopic observations on the structure of soils is practically impossible in the case of loose materials, such as sands, silts, and wet clays. Something can be done, however, with partly consolidated materials, such as dry clays, with their contained sand and silt, highly decomposed but not entirely disintegrated rocks, soil cakes from pressure, packing and heating experiments, concretions, and the like. The technic varies radically with the degree of consolidation. Concretions are frequently as hard and firmly consolidated as are many rocks and can be sectioned and mounted for microscopic study just as are rocks. It is otherwise, however, with the less consolidated types of materials, which are too fragile to stand the grinding and polishing operations incident to the making of sections unless they are strengthened by some artificial means. The means usually employed is impregnation of the material by some cementing or binding substance. Numerous substances have been used for this purpose, such as Canada balsam, paraffin, copal gum, shellac, and various commercial cements. None of them has proved perfectly satisfactory, and apparently there is no way to predict which will be best in a given case. Experience is the only guide. The writer's general preference is toward paraffin, partly because of its cheapness and availability and partly because of the ease of working the paraffin-impregnated material.

The technic of impregnating the material is simple. Drop a lump of the air-dry hardened material into a dish of melted paraffin and let it remain until no more gas bubbles are given off. This may require upward of two hours or more for a lump less than an inch in diameter. Care should be taken to keep the temperature between the melting and smoking points of the paraffin. When no more bubbles are given off the lump is removed and thoroughly cooled. It is now ready for sectioning. This can be done by carefully grinding one side to a flat and fairly smooth surface, cementing this surface to a slide by means of Canada balsam, and then grinding the opposite side until the desired thinness is reached. A cover glass cemented over the section by Canada balsam completes the operation. In the absence of grinding apparatus the same results can be attained by cutting and scraping with a pocket knife and rubbing on any sufficiently hard and smooth surface. If Canada balsam is used in place of the paraffin, greater hardness and solidity are attained.

Sand grains admixed with the material are almost certain to tear or pull out during the grinding. If they are present in large quantity they may seriously impair the quality of the section. Silts and clays, on the other hand, usually yield very fair sections.

Sections made as already described are not well adapted to the identification of the component minerals. They do, however, make it possible to observe microscopic structural features which might otherwise be unnoticed. In this respect they have the advantage of allowing the use of both transmitted and reflected light.

If for any reason whatever it is found to be impracticable to make thin, transparent sections, some information can usually be obtained by direct examination of a surface of the material in reflected light. Stratification, shrinkage cracks, pores, and the like are frequently seen with great distinctness, provided the proper magnification is used. Too high a magnification, by limiting the field of view and accentuating inconsequential details, just as frequently as not hides more than it reveals. In examinations of this kind are found some of the best illustrations of the wisdom of starting with the lowest power lenses and working up to the higher ones as the need arises.

Visibility of fine structures in reflected light is sometimes very greatly improved by varnishing the surface under examination. The surface should be as smooth and flat as the nature of the materials will allow. Ordinary shellac makes a very good varnish. The visibility can sometimes be even further improved by cementing a cover glass over the varnished surface.

Soil materials do not lend themselves to the making of sections and polished surfaces nearly so well as do rocks. The sections and surfaces that can be prepared are usually of inferior quality. Although their examination yields a certain amount of data in special cases, their usefulness is not sufficiently established to suggest any more than incidental and occasional preparations. On the other hand, the structure of soils offers a wide field for research, and if methods could be devised for collecting soils and preparing thin sections of them, comparable in quality to those of rocks, without altering or destroying the field structure, the results might be of considerable value, both from a theoretical and a practical standpoint.

ULTRAMICROSCOPES

Ultramicroscopes in general are various modifications of the dark-field illumination principle. The dark-field illuminator is simply a condenser with a blackened circle in the center of the field. This circle cuts out all direct light. The light passing the edges of the circle is reflected slantwise from the sides of the condenser to the objects. From thence it is again reflected to the eye. The effect is that of a very luminous object, a reflecting mirror, for example, on a dark background. Particles invisible in ordinary transmitted or reflected light are thus rendered brilliantly visible. For certain purposes the dark-field illuminator is dispensed with, a strong beam of light being passed through a colloidal solution in such a direction, usually at right angles, as not to enter the objective. The microscope is focused on a plane within the beam. Reflections from the suspended particles may then enter the objective and thus render the

particles visible. The effect is somewhat like that of dust motes seen in a beam of sunlight in a darkened room. The visibility is usually not quite so good as when the dark-field illuminator is used. The difference is essentially, though not entirely, a difference in degree of darkness of the background.

A certain amount of care is necessary in making mounts for ultramicroscopic observations. If the suspension is too concentrated, there will be a large amount of light scattered in various directions from the particles. Part of this light will be again and again reflected from the slide and from other particles and will reach the observer as a general illumination of the whole field of view, thus tending to nullify the advantages of the dark field. Dirty or scratched slides and cover glasses have the same effect. Colloid particles with the same refractive index as that of the mounting medium do not reflect light and are therefore invisible. Silica gel in water is an example approximative of this condition. Owing to the increased number of particles within the field, thick mounts are inclined to give the same effects as mounts of too concentrated materials, although thinner mounts might be perfectly satisfactory.

In one way or another, the ultramicroscope has an extremely wide application. In soils work it is used consistently for approximate measurements of size of soil colloidal particles and for the determination of the rates of movements of these particles in cataphoresis experiments.

FERTILIZER MATERIALS

The methods for the identification of fertilizer materials vary considerably, according to the character of the materials. The crystalline components can best be identified by a procedure exactly like that used for soil minerals. Organic components must be identified by cell structure, just as with the organic matter of soils. Amorphous and submicroscopically crystalline components, such as are frequently found both in phosphate rock and superphosphate, are often microscopically unidentifiable, and resort must be had to chemical methods. The greatest difficulty that is apt to arise in the identification of the crystalline components, especially with mixed fertilizers, is the dirtiness of the crystal surfaces. Crushing the materials has a tendency to expose new and cleaner surfaces, but too much crushing tends to dirty the surfaces thus exposed. Another difficulty arises from the large number of double salts that may be found in materials from such deposits as those of Stassfurt. The identification of these may inordinately prolong the examination without adding anything of vital importance to the information obtained. Chemical analyses of the particular fertilizer under examination are usually available to the microscopist, and he can save time by using these as general guides as to what he may reasonably expect to find. It is futile, for instance, to spend time hunting for salts of nitric acid in a mixture where all the nitrogen is in the form of ammonia. On the other hand, for example, it is sometimes desirable to know whether the potash of a given fertilizer is present as the chloride or the sulphate. If both chlorides and sulphates are present, chemistry can not well answer the question, and the petrographer is called on to identify the compounds of potash present.

MISCELLANEOUS MATERIALS

An appreciable part of the work of a petrographer in a general laboratory is apt to be the examination of miscellaneous samples originating both in the laboratory itself and from outside sources. These samples are usually of a most diverse and heterogeneous character and are submitted in almost every conceivable condition. Many of them are important. The vast majority of them, whether important or not, represent a very real desire for information on the part of the sender. Some few, of course, are inconsequential and probably represent nothing more than puerile curiosity. In any case, the petrographer's task is to take the sample as it comes and make the most of it.

The miscellaneous character of the materials precludes the possibility of any fixed procedure. Soils, rocks, glass in foods, waste products from all sorts of manufactories, fertilizers, natural deposits unfamiliar to the sender, spots on plants, crystals developed in sometimes unknown solutions, ashes of both wood and coal, electric-furnace products, crystals in plant tissue, ores and gems, boiler scale, various cements, deep-sea deposits, fibers, both natural and artificial, crystalline material extracted from soils and plants, enamel from teeth, scouring soaps, and an almost indefinite number of other substances comprise a list of materials to which no one set procedure can be applicable.

There are a few general principles, however. (1) Get all the information available concerning the sample. Usually this is apt to be meager enough, but what there is of it is sometimes of very great help. The mere knowledge of the State from which a natural sample comes, for instance, may suggest that it be tested for phosphates. (2) Find out as near as may be what information the sender wants. A vast amount of purposeless work can be done on any sample, and it is manifestly best for all concerned for the petrographer to confine his attention, within reason, to the subject at hand. (3) Do not hesitate to use chemical, physical, biological, rule of thumb, or any other methods which seem to offer a solution of the problem. The methods of petrography have an extremely wide application, but they are not all sufficient. (4) Know experts to whom the sample can be transferred when the preliminary information or tests show conclusively that the problems involved are essentially theirs.

INSPECTION OF SAMPLES FOR PURITY

Precipitates, commercial products, fractional-crystallization products, various laboratory preparations, and the like offer numerous occasions where an inspection, both rapid and economical of material, is desirable. Petrographic methods are especially suitable for such purposes. If a substance is mounted in an oil of approximately its own refractive index it becomes invisible, or nearly so, at least in some of its orientations. Other substances which may be present are not apt to have the same refractive indices and, therefore, are easily visible and readily detected. If it happens that the refractive indices are not sufficiently different to afford a ready means of differentiation, some one or more of the other optical properties

can be utilized. For example, suppose potassium chloride is to be examined. If the sample is mounted in an oil of refractive index 1.490, the potassium chloride can not be seen, whereas other substances, such as sodium chloride, will stand out prominently and can be almost immediately found. Potassium nitrate with small quantities of sodium nitrate affords a more complicated example. The maximum and minimum refractive indices of potassium nitrate are 1.335 and 1.506. Those of sodium nitrate are 1.336 and 1.587. If the sample is mounted in an oil of about 1.510, any particle in any orientation showing an index higher than this is certainly not potassium nitrate. Particles showing lower indices, however, may or may not be potassium nitrate. Changing the orientation of the particles and retesting the refractive index may give the desired differentiation. If not, the interference figures probably will.

Both inclusions of mother liquor and surface coatings stand out just as prominently as crystals of other substances, as has been previously explained. They can, therefore, be readily found and some rough idea formed as to their quantity.

It is believed that this application of petrographic methods for inspection purposes has a much wider field of usefulness than has been so far accorded it, especially in the control of commercial processes. Although the methods can not entirely replace chemical analysis, they frequently can materially reduce the number and elaborateness of the analyses. This partial substitution of rapid and inexpensive methods for slow and sometimes expensive ones is deserving of more attention than it has received.

PHASE-RULE PROBLEMS

Mixed solid components obtained at various stages in phase-rule studies frequently present almost insuperable difficulties in identification by purely chemical means. If the components are crystalline, however, petrographic methods are usually capable of solving the problem extremely rapidly and comparatively easily. In such studies the total number of possible components is strictly limited, their chemical character can be predicted, and the number possible in the solid state is known. The problem therefore simplifies itself into the question as to which components, out of a small number of possibilities, actually occur in a given mixture. Obviously, other things being equal, it is easier to answer such a question than it is to answer the more common question as to what, out of an unlimited number of possibilities, is the composition of a given mixture. As an illustration, take an actual case. A saturated solution was made of mixed NH_4Cl and KNO_3 and an excess of the salts added. These salts would react reversibly until equilibrium was reached, as represented in the following equation:

$$NH_4Cl + KNO_3 \rightleftarrows NH_4NO_3 + KCl$$

Ignoring double salts, the identification of which was not essential in the given problem, there were thus four possible compounds. One of these would be in solution, and only three could exist simultaneously in the solid phase. The question then was simply which three of the four were present in the sample under examination.

NH_4Cl and KCl are isotropic and KNO_3 and NH_4NO_3 are both strongly doubly refracting. Any isotropic substance found in the mixture was probably, therefore, either NH_4Cl or KCl, and any doubly refracting substance was probably either KNO_3 or NH_4NO_3. The refractive index of NH_4Cl is comparatively high, about 1.64, and that of KCl is comparatively low, about 1.49. These two salts could, therefore, be readily distinguished from the nitrates by their isotropy and from each other by their refractive indices. The optic axial angle of KNO_3 is extremely small, and that of NH_4NO_3 is comparatively large. These two could, therefore, be distinguished from the chlorides by their double refraction and from each other by their optic axial angles. The actual procedure was to mount the material in an oil of refractive index about 1.54. Isotropic substances having a lower index than this were, therefore, tentatively identified as KCl, and those having a higher index were identified as NH_4Cl. Doubly refracting substances with very small optic axial angles were tentatively identified as KNO_3, and those having comparatively large angles were likewise identified as NH_4NO_3. Familiarity with the properties of these salts and of the possible double salts made it feasible to observe variant properties, when present, and thus to obtain data indicative of the presence or absence of the double salts. Finally, the identifications were established definitely by such additional observations and measurements as were necessary.

The above case is comparatively simple and free from complications. The presence of double salts increases the amount of detailed work necessary before satisfactory identifications are reached, but in no wise alters the general character of the procedure which is, briefly, to make the minimum number of observations and measurements necessary to distinguish between the components possibly present. The amount of work increases as does the number of components and also as the properties of two or more components tend toward identity. Special care has to be exercised in the mounting of strongly hygroscopic salts in order to avoid the taking up of water. If the saturated solution of the salts is used as a mounting medium, a rim of oil around the edges of the cover glass acts as an effective guard against the dilution of the solution by moisture from the atmosphere.

APPENDIX

Tables 2, 3, 4, 5, and 6 were compiled solely with the idea of giving an illustration of the optical classification of crystals and of affording a limited and uncomplicated collection of data for practice on the application of the methods. For any except the very simplest determinative work, the tables of Larson (*10*) and Winchell (*19*) are practically indispensable.

TABLE 2.—*Isotropic substances* [1]

Formula	Mineral name	System and habit	Cleavage	Color	n
NaF		Isometric	(100)	Colorless	1.336
CaF_2	Fluorite	Cubes	(111) perfect	Variable	1.434
$NaAl(SO_4)_2.12H_2O$		do		do	1.4388
$KAl(SO_4)_2.12H_2O$	Alum	Octahedral	None	Colorless	1.4562
$(NH_4)Al(SO_4)_2.12H_2O$		Isometric		do	1.4594
SiO_2	Cristobalite	Pseudo-isometric or octahedral		White	1.486.
$Na_2O.Al_2O_3.4SiO_2.2H_2O$	Analcite	(211)	(100) trace	Colorless	1.487
KCl	Sylvite	Plagihedral	Cubic, perfect	do	1.490
$K_2O.Al_2O_3.4SiO_2$	Leucite	Pseudo-isometric (211)	Imperfect	do	1.509
$K_2Mg_2(SO_4)_3$	Langbeinite	Highly modified tetrahedral		do	1.535
$NaCl$	Halite	Cubes	Cubic, perfect	do	1.544
KBr		Isometric		do	1.559
$Sr(NO_3)_2$		do		do	1.567
$Ba(NO_3)_2$	Nitrobarite	Isometric or octahedral		do	1.571
NH_4Cl		Isometric	(111) imperfect	do	1.642
KI		do		do	1.677
$Mg_3Al_2(SiO_4)_3$	Pyrope-garnet	(110), (211)	None	Red	1.705–1.742
$MgAl_2O_4$	Spinel	Octahedral	(111) imperfect	Red and variable	1.723–1.75
$Ca_3Al_2(SiO_4)_3$	Grossularite-garnet	(110), (211)	None	Variable	1.735
MgO	Periclase	Cubes	(100) perfect, (111) poor	Colorless	1.736
As_2O_3	Arsenolite	Octahedral		White	1.755
$(Mg,Fe)Al_2O_4$	Pleonaste	(111), rarely (100)	None	Black	1.77
$Fe_3Al_2(SiO_4)_3$	Almandite-garnet	(110), (211)		Dark red	1.778–1.83
$Pb(NO_3)_2$		Isometric		Colorless	1.7838
$(Mn,Fe)_3Al_2(SiO_4)_3$	Spessartite-garnet	(110), (211)	None	Reddish	1.811
CaO	Cubes	(100) perfect		Colorless	1.83
$Ca_3Fe_2(SiO_4)_3$	Andradite-garnet	(110), (211)	Conchoidal	Variable	1.895
ZnS	Sphalerite	Tetrahedral	(110) perfect	Colorless and variable	2.37

[1] Remain dark on rotation between crossed Nicols and do not give an interference figure.

TABLE 3.—*Uniaxial positive substances* [1]

Composition	Mineral name	System and habit	Cleavage	Color	ϵ_D	ω_D	$\epsilon-\omega$
$Na_3PO_4.12H_2O$		Trigonal			1.4524	1.4458	0.0066
$(Ca, Na_2)Al_2(SiO_3)_4.6H_2O$	Chabazite-zeolite	Pseudo-trigonal, cubic	(10$\bar{1}$1) distinct	White	1.482	1.480	.002
$NaK_3(SO_4)_2$		Trigonal			1.4996	1.4901	.0095
$(K, Na)_2SO_4$	Aphthitalite	Trigonal, tabular, rhombic	(10$\bar{1}$0) rather distinct (0001) imperfect.	White	1.499	1.491	.008
$K_2Al_2(SiO_3)_4$	Leucite	Pseudo-isometric (211)	(110) poor	Colorless	1.509	1.508	.001
SiO_2	Quartz	Trigonal, hexagonal, prisms and pyramids.	None	do	1.553	1.544	.009
$Fe_2(SO_4)_3.9H_2O$	Coquimbite	Trigonal	(10$\bar{1}$0), (10$\bar{1}$1), (01$\bar{1}$1) imperfect.	White, yellow, violet	1.556	1.550	.006
$K(AlO_2H_2)_3(SO_4)_2$	Alunite	Trigonal tabular (0001), or cubic.	(0001) distinct	White	1.592	1.572	.020
Zn_2SiO_4	Willemite	Trigonal	(0001) variable (11$\bar{2}$0) variable.	White, green, red, brown, and variable.	1.723	1.694	.029
$CaWO_4$	Scheelite	Tetragonal, octahedral, or tabular.	(111) distinct	White, yellow, brown, gray	1.934	1.918	.016
$ZrSiO_4$	Zircon	Tetragonal, short prisms and pyramids.	(110) rare	Colorless, yellow, brown, gray, pink, and variable.	1.968–2.015	1.923–1.960	0.045–.055
Hg_2Cl_2	Calomel	Tetragonal	(100), (111) rather distinct.	Colorless	2.656	1.973	.683
SnO_2	Cassiterite	Tetragonal	(100), (111) imperfect	Brown, black, gray, white	2.093	1.997	.096
ZnS	Wurtzite	Hexagonal, short prisms, lamellar (0001).	(11$\bar{2}$0) easy, (0001) difficult	Variable	2.378	2.356	.022
TiO_2	Rutile	Tetragonal prismatic	(100), (110) distinct	Yellow, red, brown, and variable.	2.903	2.616	.287
CSi [2]	Moissanite	Hexagonal plates (0001)		Green to black	2.697	2.654	.043
HgS	Cinnabar	Hexagonal	(10$\bar{1}$0) perfect	Cochineal red	3.201	2.854	.347

[1] Give a uniaxial cross and are optically positive with the gypsum plate or quartz wedge.
[2] Pleochroism (p. 62) ω=light blue, ϵ=deep indigo blue.

TABLE 4.—*Uniaxial negative substances* [1]

Composition	Mineral name	System and habit	Cleavage	Color	ω_D	ϵ_D	$\omega-\epsilon$
$(Na_2, Ca)\ Al_2\ (SiO_3)_4.6H_2O$	Gmelinite-zeolite	Trigonal	$(10\bar{1}0)$ easy	Colorless	1.465	1.464	0.001
Do	Chabazite	Trigonal cubic habit	$(10\bar{1}1)$ distinct	White	1.480	1.478	.002
SiO_2	Cristobalite	Tetragonal and pseudo-isometric, octagonal.		Colorless	1.487	1.484	.003
$Na_2Al_2(SiO_3)_4.2H_2O$	Analcite	Pseudo-isometric (211)	Cubic, trace	do	1.487	1.486	.001
$MgNa_2(SO_4)_2.2\frac{1}{2}H_2O$	Loewite	Trigonal	(0001) distinct	White	1.490	1.471	.019
KH_2PO_4		Tetragonal			1.5095	1.4684	.0411
$NiSO_4.6H_2O$		do		Green	1.5109	1.4873	.0236
$NH_4H_2PO_4$		do			1.5246	1.4792	.0454
$Na_2Al_2(SiO_4)_2$	Nephelite	Hexagonal	$(10\bar{1}0)$, (0001) imperfect	Colorless	1.542	1.538	.004
$BE_3Al_2(SiO_3)_6$	Beryl	Hexagonal prisms	(0001) imperfect	Colorless, green, blue, yellow, and variable.	1.568–1.598	1.564–1.590	.004–.008
$NaNO_3$	Soda niter	Trigonal	$(10\bar{1}1)$ perfect	White	1.587	1.336	.251
$K_2O.4(Mg,Fe)O.$ $2(Al,Fe)_2O_3.6SiO_2.H_2O.$	Biotite	Monoclinic, hexagonal plates.	(001) microscopic	Brown, black, and green	1.600		Strong.
$Cag(PO_4)_6.Ca(F,Cl)_2$	Apatite	Hexagonal prisms	(0001) imperfect	Colorless and variable	1.634	1.631	.003
Iron-rich biotite	Lepidomelane	Monoclinic scales	(001) microscopic	Black	1.64		.050
$CaCO_3$	Calcite	Trigonal	$(10\bar{1}1)$ perfect	Colorless and variable	1.658	1.486	.172
$CaMg(CO_3)_2$	Dolomite	Trigonal rhombic	$(1\bar{1}01)$ perfect	White	1.681	1.500	.181
$Na_2O,(Fe,Mg,Cr)O,Al_2O_3,$ $SiO_2,B_2O_3,H_2O.$	Tourmaline [2]	Hexagonal prisms	None	Black and variable	1.687	1.641	.046
$Ca(Mg,Fe)(CO_3)_2$	Dolomite	Trigonal rhombic	$(10\bar{1}1)$ perfect	White	1.695	1.510	.185
$MgCO_3$	Magnesite	Trigonal massive	do	Colorless, white, and variable	1.700	1.509	.191
$(Mg,Fe)CO_3$	do	Trigonal rhombic	do	White	1.726	1.527	.199
Al_2O_3	Corundum	Trigonal	(0001) perfect parting	Red, blue, and variable	1.768	1.760	.008
$ZnCO_3$	Smithsonite	do	$(10\bar{1}1)$ perfect	Colorless and variable	1.818	1.618	.200
$MnCO_3$	Rhodochrosite	do	$(10\bar{1}0)$ perfect	Pink	1.817	1.597	.220
$(Mn,Fe)CO_3$	do	Trigonal rhombic	$(1\bar{1}01)$ perfect	do	1.826	1.605	.221
$(Fe,Mg)CO_3$	Siderite	Trigonal	do	Colorless to brown	1.830	1.596	.234
$(Fe,Mn)CO_3$	do	do	do	Colorless and variable	1.849	1.615	.234
$FeCO_3$	do	do	do	do	1.855–1.875	1.613–1.633	.242
PbO_2	Plattnerite	Tetragonal		Black	2.8_{Li}		
TiO_2	Anatase	Tetragonal octahedral	(001), (111) perfect	Brown and variable	2.554	2.493	.061
PbO	Litharge	Tetragonal tabular (001)	(110) perfect	Red and variable	2.665_{Li}	2.535_{Li}	.130

[1] Give a uniaxial cross and are optically negative with the gypsum plate or quartz wedge.
[2] Pleochroism strong, ω = green to bluish green, ϵ = yellow.

TABLE 5.—*Biaxial positive substances* [1]

Substance	System	α	β	γ	Color pleochroism	2V	Dispersion	Orientation
						° ′		
Na_3AlF_6 (cryolite)	Monoclinic		1.364		Color variable	43	$\rho<\upsilon$	Axial plane⊥(010). $Z\wedge c=43°\ 54'$ in acute $\angle\beta$.
$Na_2HPO_4.7H_2O$	do	1.441	1.442	1.453		38 50	Not perceptible	Axial plane⊥b (010). $Z\wedge c=72°$ in acute $\angle\beta$.
$K_2Mg(SO_4)_2.6H_2O$ (picromerite)	do	1.461	1.463	1.476	White	48		Axial plane b (010). $Z\wedge c=103°\ 38'$. $Z\wedge a=1°\ 10'$. $X\wedge c=-1°$.
$(NH_4)_2Mg(SO_4)_2.6H_2O$	do	1.472	1.473	1.479		51 11		Axial plane b (010). $Z\wedge c=94°\ 58'$. $Z\wedge a=12°\ 8'$.
Na_2SO_4 (thenardite)	Orthorhombic	1.464	1.474	1.485	White and variable	84	$\rho>\upsilon$, weak	$X=b$. $Y=c$.
$FeSO_4.7H_2O$ (melanterite)	Monoclinic	1.471	1.478	1.486	Green, yellow	86	do	$Y=b$. $Z\wedge c=-61°$.
$K_2Fe(SO_4)_2.6H_2O$	do	1.476	1.482	1.497		67 7		Axial plane b (010). $Z\wedge c=101°\ 57'$. $Z\wedge a=2°\ 35'$.
K_2SO_4 (arcanite)	Orthorhombic	1.494	1.495	1.497		67	$\rho>\upsilon$, moderate	$X=b$. $Z=c$.
$NH_4MgPO_4.6H_2O$ (struvite)	do	1.495	1.496	1.504	Colorless and variable	37	$\rho>\upsilon$, strong	$Z=b$. $X=c$.
$KAl(SiO_3)_2$ (leucite)	do		1.508		do	(2)		$Z=a$.
$Ca_2H_2(PO_4)_2$ (monetite)	Triclinic	1.515	1.518	1.525	do	(2)		X emerges from (100).
$CaSO_4.2H_2O$ (gypsum)	Monoclinic	1.520	1.523	1.530	White	58	$\rho>\upsilon$, perceptible	$Y=b$. $X\wedge c=37\frac{1}{2}°$.
$(NH_4)_2SO_4$ (masceagnite)	Orthorhombic	1.521	1.523	1.533	Colorless and variable	52	$\rho>\upsilon$, feeble	$Z=a$. $X=c$.
$NaAlSi_3O_8$ (albite)	Triclinic	1.525	1.529	1.536	Colorless	74	$\rho<\upsilon$, weak	On (010) $X\wedge(001)=24°$. On (001) $X\wedge(010)=3\frac{1}{2}°$.
$MgSO_4,H_2O$ (kieserite)	Monoclinic	1.523	1.535	1.586	White	57	$\rho>\upsilon$, moderate	$Y=b$. $X\wedge c=76\frac{1}{2}°$.
$Ca_2H_2(PO_4)_2.4H_2O$ (brushite)	do	1.539	1.545	1.551	do	86		$Z=b$.
Na, Ca feldspar (andesine)	Triclinic	1.550	1.553	1.557	Colorless and variable	88		On (010) $X\wedge(001)=8°$. On (010) $X\wedge(010)=2°$.
$CaC_2O_4.H_2O$ (whewellite)	Monoclinic	1.491	1.555	1.650	Colorless	84	$\rho<\upsilon$, weak	$X=b$. $Z\wedge c=-11°$.
Ca, Na feldspar (labradorite)	Triclinic	1.559	1.563	1.568	do	79		On (010) $X\wedge(001)=21°$. On (001) $X\wedge(010)=9°$.
$CaSO_4$ (anhydrite)	Orthorhombic	1.571	1.576	1.614	do	42	$\rho<\upsilon$	$X=c$. $Z=a$.
Fe, Mg, Al (silicate, hydrated, prochlorite).	Monoclinic	1.606	1.606	1.610	Green	(4)	$\rho<\upsilon$, perceptible	Z near c.
$BaSO_4$ (barite)	Orthorhombic	1.636	1.637	1.648	White	37½	$\rho<\upsilon$, weak	$X=c$. $Z=a$.

$BaCl_2.2H_2O$	Monoclinic	1.635	1.646	1.660		83	46		Axial plane (010). $Z \wedge c = 8°$ in obtuse $\angle \beta$.
Al_2SiO_5 (sillimanite)	Orthorhombic	1.638	1.642	1.653	Colorless, gray	20		$\rho > v$, strong	$X = b$. $Z = c$.
$(Mg, Fe)_2SiO_4$ (olivine)	do	1.662	1.680	1.699	Green, brown, and variable	(3)		$\rho < v$	$X = b$. $Z = a$.
$Ca(Mg, Fe)_2(Al, Fe)_2(SiO_4)_3$ (augite)	Monoclinic	1.698	1.704	1.723	Green and variable	60		do	$Y = b$. $Z \wedge c = 38°$ to $54°$.
$(Ce, La, Di)_2(PO_4)_2$ (monazite)	do	1.786	1.788	1.837	Red, brown, and variable	14		$\rho < v$, weak	$X = b$. $Z \wedge c = 2°$.
S (sulphur)	Orthorhombic	1.950	2.043	2.240	Yellow	69		$\rho < v$	$X = a$. $Z = c$.

[1] Give hyperbolæ as interference figure, and are optically positive with gypsum plate or quartz wedge.
[2] Small.
[3] Large.
[4] Very small.

TABLE 6.—*Biaxial negative substances* [1]

Substance	System	α	β	γ	Color pleochroism	$2V$		Dispersion	Orientation
						°	′		
$Na_2SO_4.10H_2O$ (mirabilite)	Monoclinic	1.394	1.396	1.398	White	76		$\rho < v$	$X = b$ or $Y = b$. $Z \wedge c = 30°$.
$Na_2HPO_4.12H_2O$	do	1.432	1.436	1.437		56	43	Distinct, inclined	Axial plane b (010). $X \wedge c = 31°$ in acute $\angle \beta$.
$Na_2CO_3.10H_2O$ (natron)	do	1.405	1.425	1.440	White	71		$\rho > v$, perceptible	$X = b$.
$MgSO_4.7H_2O$ (epsomite)	Orthorhombic	1.433	1.455	1.461	do	52		$\rho < v$, weak	$X = a$. $Z = b$.
$NaH_2PO_4.2H_2O$	do	1.440	1.463	1.482	do	82	50		Axial plane b (010). $X \parallel c$.
$Na_2B_4O_7.10H_2O$ (borax)	Monoclinic	1.447	1.470	1.472	do	39		$\rho > v$, strong	$X = b$. $Z \wedge c = 56.9°$.
$NaH_2PO_4.H_2O$	Orthorhombic	1.456	1.485	1.487		29	22		Axial plane b (010). $X \parallel a$.
$K_2Mg(SO_4)_2.4H_2O$ (leonite)	Monoclinic	1.483	1.487	1.490	Colorless	86		$\rho < v$	$Y = b$. $Z \wedge c$ = small.
$Na_2Mg(SO_4)_2.4H_2O$ (bloedite)	do	1.486	1.488	1.489	do	71		$\rho < v$, strong	$Y = b$. $X \wedge c = 41.1°$.
KNO_3 (niter)	Orthorhombic	1.334	1.505	1.506	do	7		do	$X = c$. $Z = b$.
$MgSO_4.KCl.3H_2O$ (kainite)	Monoclinic	1.494	1.505	1.516	do	85		$\rho > v$, small	$Y = b$. $X \wedge c = -8°$.
$Na_2CO_3.H_2O$ (thermonatrite)	Orthorhombic	1.420	1.506	1.524	White	48		$\rho < v$, weak	
$K_2Ca(SO_4)_2.H_2O$ (syngenite)	Monoclinic	1.500	1.517	1.518	do	27		$\rho < v$, very strong	$Z = b$. $Y \wedge c = -2.3°$.

[1] Give hyperbolæ as interference figure and are optically negative with gypsum plate or quartz wedge.

TABLE 6.—*Biaxial negative substances*—Continued

Substance	System	α	β	γ	Color pleochroism	$2V$	Dispersion	Orientation
						° ′		
$KAlSi_3O_8$ (orthoclase)	Monoclinic	1.518	1.524	1.526	White, colorless pink, and variable.	0–70	Weak	Y or $Z=b$. $X \wedge a=5°$.
$KAlSi_3O_8$ (microcline)	Triclinic	1.522	1.526	1.530	do	83	$\rho>v$, weak	Extinction on (001) = 15°. Extinction on (010) = 5°–6°.
(Na, K)$AlSi_3O_8$ (anorthoclase)	do	1.523	1.529	1.531	do	32–54	do	Extinction on (001) = 1°–6°. Extinction on (010) = 6°–10°.
$Na_2Ca(SO_4)_2$ (glauberite)	Monoclinic	1.515	1.532	1.536	Colorless	7	$\rho>v$, strong	$Z=b$. $Y \wedge c=14.2°$.
$CuSO_4.5H_2O$ (chalcanthite)	Triclinic	1.516	1.539	1.546	Blue	56	$\rho<v$, perceptible	
Na, Ca, feldspar (oligoclase)	do	1.539	1.543	1.547	Colorless	86	$\rho<v$, weak	On (010) $X \wedge (001) = 6°$. On (001) $X \wedge (010) = 1°$.
$(NH_4)_2C_2O_4.H_2O$ (oxammite)	Orthorhombic	1.439	1.547	1.595	White	60	$\rho<v$.	$X=c$. $Y=a$.
$2CaSO_4.MgSO_4.K_2SO_4.2H_2O$ (polyhalite)	Triclinic	1.548	1.562	1.567	Flesh red, yellow, and variable	70		
$Mg_3Si_2O_7.2H_2O$ (serpentine)	Orthorhombic	1.560	1.570	1.571	Green	20–90		$X=b$. $Z=c$.
K, Mg, Fe, Al (silicate, hydrated, biotite)	Monoclinic	1.541	1.574	1.574	Black and variable	0–50	$\rho<v$, perceptible	$Y=b$. $X \wedge c=3°$.
$CaAl_2Si_2O_8$ (anorthite)	Triclinic	1.576	1.584	1.588	White	77	$\rho<v$	On (010) $X \wedge (001) = -37°$. On (001) $X \wedge (010) = -40°$.
$K_2Al_6Si_6O_{22}.2H_2O$ (muscovite)	Monoclinic	1.561	1.590	1.594	Colorless	40	$\rho>v$, perceptible	$Z=b$. $X \wedge c=0°$.
Al, Fe, Mg, Ca, Na (silicate, hornblende)	do	1.629	1.642	1.653	Green, black, brown, and variable.	84	$\rho<v$	$Y=b$. $Z \wedge c=15°–25°$.
$CaCO_3$ (aragonite)	Orthorhombic	1.531	1.682	1.686	Colorless	19	$\rho<v$, small	$X=c$. $Z=b$.
Al_2SiO_5 (cyanite)	Triclinic	1.712	1.720	1.728	Blue, colorless, and variable	82	$\rho>v$, slight	X almost $\perp$ (100). $Z \wedge c=-30°$.
Ca, Al, Fe (silicate, epidote)	Monoclinic	1.729	1.754	1.768	Green	(2)	$\rho>v$, rather strong	$Y=b$. $X \wedge c=-2.5°$.

[2] Large.

LITERATURE CITED

(1) ANDERSON, M. S., and FRY, W. H.
1920. SOLID PHASES OBTAINED BY THE EVAPORATION OF CERTAIN SOIL EXTRACTS. Jour. Indus. and Engin. Chem. 12: 663–669.

(2) CHAMOT, E. M., and MASON, C. W.
1930. HANDBOOK OF CHEMICAL MICROSCOPY. v. 1, 474 p., illus. New York and London.

(3) COUCH, J. F.
1925. LUPINE STUDIES. IV. ISOLATION OF D-LUPANINE FROM LUPINUS KINGII (S. WATSON). Jour. Amer. Chem. Soc. 47: 2584–2587.

(4) DANA, E. S.
1916. A TEXT-BOOK OF MINERALOGY, WITH AN EXTENDED TREATISE ON CRYSTALLOGRAPHY AND PHYSICAL MINERALOGY. New ed., entirely rewritten and enlarged, 593 p., illus. New York.

(5) FRY, W. H.
1914. IDENTIFICATION OF COMMERCIAL FERTILIZER MATERIALS. U. S. Dept. Agr. Bul. 97, 13 p.

(6) HENDRICKS, S. B., and FRY, W. H.
1930. THE RESULTS OF X-RAY AND MICROSCOPICAL EXAMINATIONS OF SOIL COLLOIDS. Soil Sci. 29: 457–479, illus.

(7) JOHANNSEN, A.
1918. MANUAL OF PETROGRAPHIC METHODS. Ed. 2, 649 p., illus. New York and London.

(8) KEENAN, G. L.
1924. THE OPTICAL PROPERTIES OF SOME AMINO ACIDS. Jour. Biol. Chem. 62: 163–172, illus.

(9) KELLY, W. P., DORE, W. H., and BROWN, S. M.
1931. THE NATURE OF THE BASE-EXCHANGE MATERIAL OF BENTONITE, SOILS, AND ZEOLITES, AS REVEALED BY CHEMICAL INVESTIGATION AND X-RAY ANALYSIS. Soil Sci. 31: 25–55.

(10) LARSEN, E. S.
1921. THE MICROSCOPIC DETERMINATION OF THE NONOPAQUE MINERALS. U. S. Geol. Survey Bul. 679, 294 p., illus.

(11) MCCAUGHEY, W. J., and FRY, W. H.
1913. THE MICROSCOPIC DETERMINATION OF SOIL-FORMING MINERALS. U. S. Dept. Agr., Bur. Soils Bul. 91, 100 p., illus.

(12) MERWIN, H. E.
1913. MEDIA OF HIGH REFRACTION FOR REFRACTIVE INDEX DETERMINATIONS WITH THE MICROSCOPE; ALSO A SET OF PERMANENT STANDARD MEDIA OF LOWER REFRACTION. Jour. Wash. Acad. Sci. 3: 35–40, illus.

(13) MIERS, Sir H. A.
1929. MINERALOGY; AN INTRODUCTION TO THE SCIENTIFIC STUDY OF MINERALS. Ed. 2, rev. by H. L. Bowman. 658 p., illus. London.

(14) SALOMON, W.
1896. UEBER DIE BERECHNUNG DES VARIABLEN WERTHES DER LICHTBRECHUNG IN BELIEBIG ORIENTIRTEN SCHNITTEN OPTISCH EINAXIGER MINERALIEN VON BEKANNTER LICHT- UND DOPPELBRECHUNG. Ztschr. Kristallographie u. Mineralogie 26: [178]–187, illus.

(15) SHORT, M. N.
1931. MICROSCOPIC DETERMINATION OF THE ORE MINERALS. U. S. Geol. Survey Bul. 825, 204 p., illus.

(16) STORY-MASKELYNE, M. H. N.
1895. CRYSTALLOGRAPHY; A TREATISE ON THE MORPHOLOGY OF CRYSTALS. 521 p., illus. Oxford.

(17) WATSON, W.
1905. A TEXT-BOOK OF PHYSICS. Ed. 4, 929 p., illus. New York. London [etc.].

(18) WHERRY, E. T.
1918. THE APPLICATION OF OPTICAL METHODS OF IDENTIFICATION TO ALKALOIDS AND OTHER ORGANIC COMPOUNDS. U. S. Dept. Agr. Bul. 679, 9 p.

(19) WINCHELL, A. N.
1931. THE MICROSCOPIC CHARACTERS OF ARTIFICIAL INORGANIC SOLID SUBSTANCES OR ARTIFICIAL MINERALS. Ed. 2, 403 p., illus. New York and London.

(20) WRIGHT, F. E.
1911. THE METHODS OF PETROGRAPHIC-MICROSCOPIC RESEARCH, THEIR RELATIVE ACCURACY AND RANGE OF APPLICATION. 204 p., illus. Washington, D. C. (Carnegie Inst. Wash. Pub. 158.)

U. S. GOVERNMENT PRINTING OFFICE: 1933

TECHNICAL BULLETIN No. 343 February, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

SPECIFIC GRAVITY AND RELATED PROPERTIES OF SOFTWOOD LUMBER

By EDWARD C. PECK [1]

Associate Wood Technologist, Forest Products Laboratory,[2] Branch of Research, Forest Service

CONTENTS

	Page
Introduction	1
Factors that influence the weight of wood	2
Wood substance	2
Spring wood and summer wood	2
Moisture	2
Extractives	4
Compression wood	4
Decay	4
Growth conditions	4
Position in the bole	5
Geographical location	5
Method of experimentation	5
Scope	5
Collection of specimens	9
Specific-gravity determinations	9
Discussion of results	9
Specific-gravity data	9
Species and regional comparisons	10
Mill comparisons	14
Comparison of average specific gravity of different qualities of lumber of the same species	15
Comparison of present data with previously published data	16
Relation between specific gravity and various properties	17
Mechanical properties	17
Drying rate	18
Equilibrium moisture content	19
Shrinkage	19
Woodworking properties	19
Painting properties	19
Gluing properties	20
Raised grain	20
Shipping weights	20
Treating properties	22
Fuel value	22
Heat conductivity	22
Pulp yield	22
Summary	22
Literature cited	23

INTRODUCTION

Lumber is frequently compared in terms of its weight, that is, a thousand board feet of lumber of a given species weighs so many pounds. For exact comparisons, however, a more definite term must be used. In this bulletin, therefore, the term specific gravity is used. Specific gravity as used here is based on the weight of the oven-dry wood and the volume when green.

The average specific gravity and the range in specific gravity for the wood of a species are, in the absence of actual test data, criteria of the character of the wood, and may be used to estimate the strength properties; wearing qualities; shrinkage characteristics; and woodworking, painting, gluing, and nail-holding properties; as well as the shipping weights; fuel value; heat conductivity; and pulp yields. Specific-gravity values may be converted into any other form for practical use, provided the moisture-shrinkage relation is known.

[1] Acknowledgment is made of cooperation received in this study from the National Lumber Manufacturers' Association and from various members of the Forest Products Laboratory.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

150473°—33——1

In the past many data have been gathered on the specific gravity of wood, but usually on a small number of logs or trees. It is the purpose of this bulletin to present specific-gravity data, based on tests of sections of boards collected at sawmills throughout the United States, for the lumber of 14 of the commercially important softwood (coniferous) species. The principal difference between this study and former studies is the manner of selecting the test specimens. The data presented here are classified according to the commercial terms or designations of the lumber and not according to botanical classification, although in most instances the two are approximately the same.

In addition to presenting the specific-gravity values for lumber, an effort is made to indicate their effect on the various properties and characteristics of the wood. The effect of specific gravity on some of the properties of wood has been determined, but on many others it is still unknown.

FACTORS THAT INFLUENCE THE WEIGHT OF WOOD

WOOD SUBSTANCE

The most important of the factors that determine the specific gravity of wood is the wood substance itself. The woody structure is in the form of a honeycomb of cells, the walls of which are composed mainly of cellulose and lignin. The specific gravity of any wood, as far as the wood substance is concerned, is proportional to the relation of the volume of the cell walls to that of the cavities or voids, inasmuch as the specific gravity of the cell-wall substance is approximately the same in all woods.

SPRING WOOD AND SUMMER WOOD

In many species there is a marked difference between the wood cells that are formed early in the growing season and those that are formed later. The different types of seasonal growth are known as spring wood and summer wood. The spring-wood cells are large and thin walled, whereas the summer-wood cells are smaller and thick walled, when viewed in cross section. In some species, however, there is no strong contrast between the cells of the spring wood and those of the summer wood. In those woods having very dense summer wood the width of these bands of cells, viewed in cross section, as compared with the total width, permits a segregation of classes according to specific gravity.

MOISTURE

The weight per unit volume of wood at any given time is influenced by the amount of moisture the wood contains. At moisture-content conditions below the fiber-saturation point a change in moisture content has slight effect on the weight per unit volume because the increase or decrease in weight is to a large extent offset by a corresponding increase or decrease in volume. (The condition at which the cell cavity is empty while the cell walls are still saturated is called the "fiber-saturation point.") Above the fiber-saturation point the

weight per unit volume is greatly influenced by a change in moisture content because there is no offsetting change in volume. In all of the softwood species dealt with in this bulletin the addition of

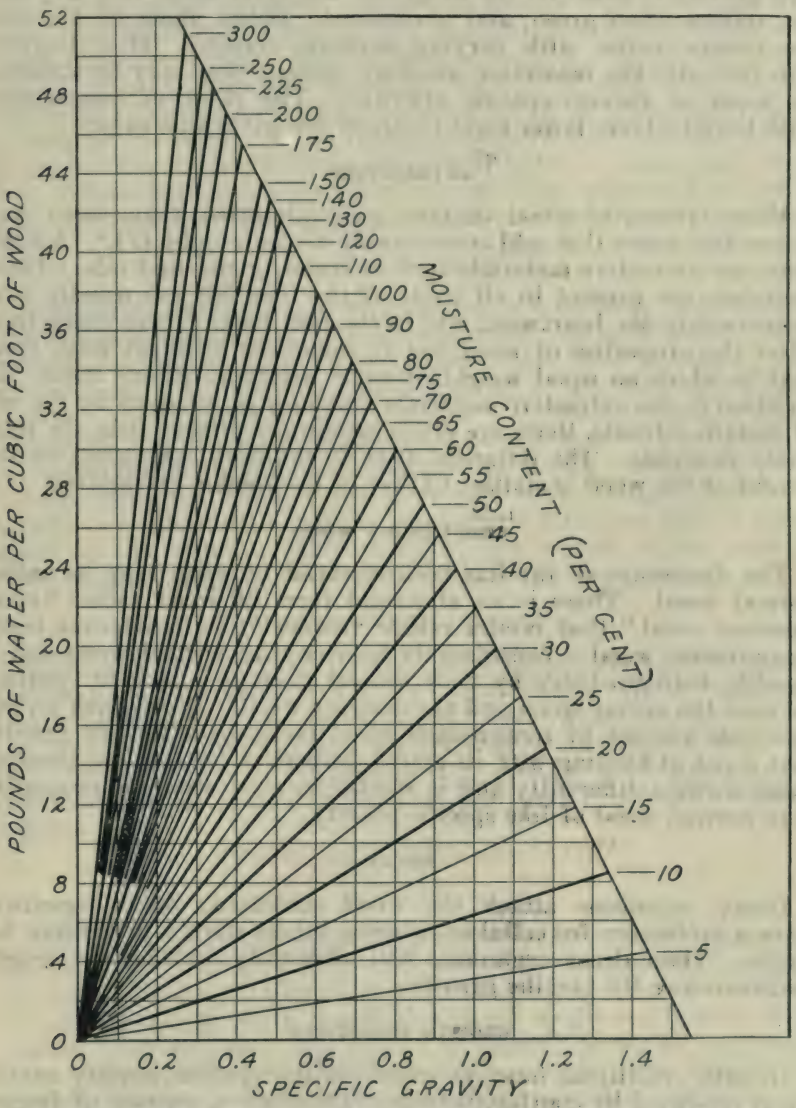


FIGURE 1.—Pounds of water per cubic foot for wood of a given specific gravity and moisture content; also the moisture content of wood at various specific gravities, when completely saturated. The specific gravity for use with this figure is always based on the weight of the oven-dry wood and the volume at whatever moisture content it may be

moisture increases the weight per unit volume because the increase in weight is greater than the corresponding increase in volume.

Figure 1 shows the amount of water in pounds per cubic foot in wood of any specific gravity at any moisture content, where the

specific gravity is based on the weight of the oven-dry wood and the volume of the wood at whatever moisture content it may be.[3] Under all conditions of moisture content above about 25 per cent, the specific gravity is based on the weight of the wood when oven dry and the volume when green, and is constant. Below about 25 per cent the volume varies with varying moisture content. This diagram also indicates the maximum moisture content that may be attained by wood of various specific gravities. The point of intersection with the line from lower right to upper left gives this value.

EXTRACTIVES

Many species of wood contain materials other than wood substance and water that add considerably to the weight (*7*).[4] Among these are extractive materials such as resins, gums, and oils. These materials are present in all parts of the tree, but are usually preponderant in the heartwood and in the butt logs. These extractives affect the properties of wood, but in somewhat different ways from that in which an equal weight of wood substance affects them. In addition to the extractive materials that may be removed by the use of certain solvents, there are other substances present that are relatively insoluble. The influence of these insoluble substances on the weight of the wood is similar to that of the soluble extractives.

COMPRESSION WOOD

The discussion so far has been confined to what may be called normal wood. There is an abnormal form of wood called "compression wood" that occurs rather frequently in coniferous trees. Compression wood is considerably heavier than normal wood and is usually distinguishable by wide annual rings and lack of contrast between the spring wood and the summer wood. Wood with an appreciable amount of compression wood possesses a specific gravity that is out of keeping with its actual properties, because compression wood shrinks differently and is weaker in most strength properties than normal wood of like specific gravity.

DECAY

Decay organisms attack the wood substance; some organisms show a preference for cellulose, whereas others show a preference for lignin. These decay organisms will ultimately decrease the weight and therefore the specific gravity.

GROWTH CONDITIONS

Growth conditions have an effect on the specific gravity of the wood produced by coniferous trees. There are a number of factors included in the term "growth conditions," and it is often difficult to isolate them so that the effect of any one may be definitely demonstrated. Much research has been conducted on this subject, and in some instances it has been possible to show the effect of certain factors on specific gravity.

---

[3] Figure 1 was prepared by J. D. MacLean, Forest Products Laboratory.
[4] Italic numbers in parentheses refer to Literature Cited, p. 23.

In the southern pines the wood of high specific gravity is rarely found in very wide or in very narrow growth rings, but usually in rings of medium width (*11*). Southern pine trees growing in open stands when young or in crowded stands when old usually produce wood of low specific gravity. In second-growth stands the trees with large crowns contain wood of low specific gravity, and those with smaller crowns contain wood of high specific gravity unless crowding of the stand has been continued for such a long time that the specific gravity of the wood has been decreased by suppression of the growth of the trees. Wood of the greatest specific gravity is produced by normal trees growing in normal stands. These rules apply only if the soil is of sufficient fertility and if the supply of soil water is ample, especially during the period of summer-wood formation.

POSITION IN THE BOLE

The specific gravity of the wood varies in accordance with its position in the bole of the tree. This position resolves itself into two components, height above the ground and distance from the pith. At a given height in the tree the specific gravity of the wood may remain constant, may increase, or may decrease with distance from the pith. Along the bole of the tree there is a tendency for the wood of many species to become lower in specific gravity as the distance above the ground increases. In a study of redwood (*7*) the butt logs on an average were found to contain wood the specific gravity of which, based on the volume when green and the weight of the oven-dry wood, was 15 per cent greater than that of the top logs.

GEOGRAPHICAL LOCATION

Some species that are widely distributed geographically show different characteristics in different parts of their ranges. Although these differences are due to variation in growth conditions, some of the growth conditions in turn are affected by the geographical location. With certain of the species it is possible to demonstrate the difference in the specific gravity of the wood growing in different regions.

METHOD OF EXPERIMENTATION

SCOPE

The data in this bulletin are based on specific-gravity determinations made on 22,838 sections of boards, termed specimens, collected at 49 sawmills from 14 kinds of softwood lumber. In some instances lumber of two species is included under a single commercial designation. For example, the term "shortleaf" includes the lumber from both loblolly and shortleaf pines, and the term "white fir" includes the lumber from lowland white fir as well as white fir. The term "longleaf" may apply to true longleaf and the denser pieces of the other southern-pine species. Specimens of the same kind of lumber were sometimes collected in different geographical regions. The location of the sawmills and the kinds of lumber sampled at each is shown on the map in Figure 2.

Upper and lower grades of lumber and thicknesses up to and including 2 inches were studied. The specimens were usually selected

at random so that the proportion of heartwood and sapwood would approximate that actually in the lumber. Table 1 gives the number and character of the specimens.

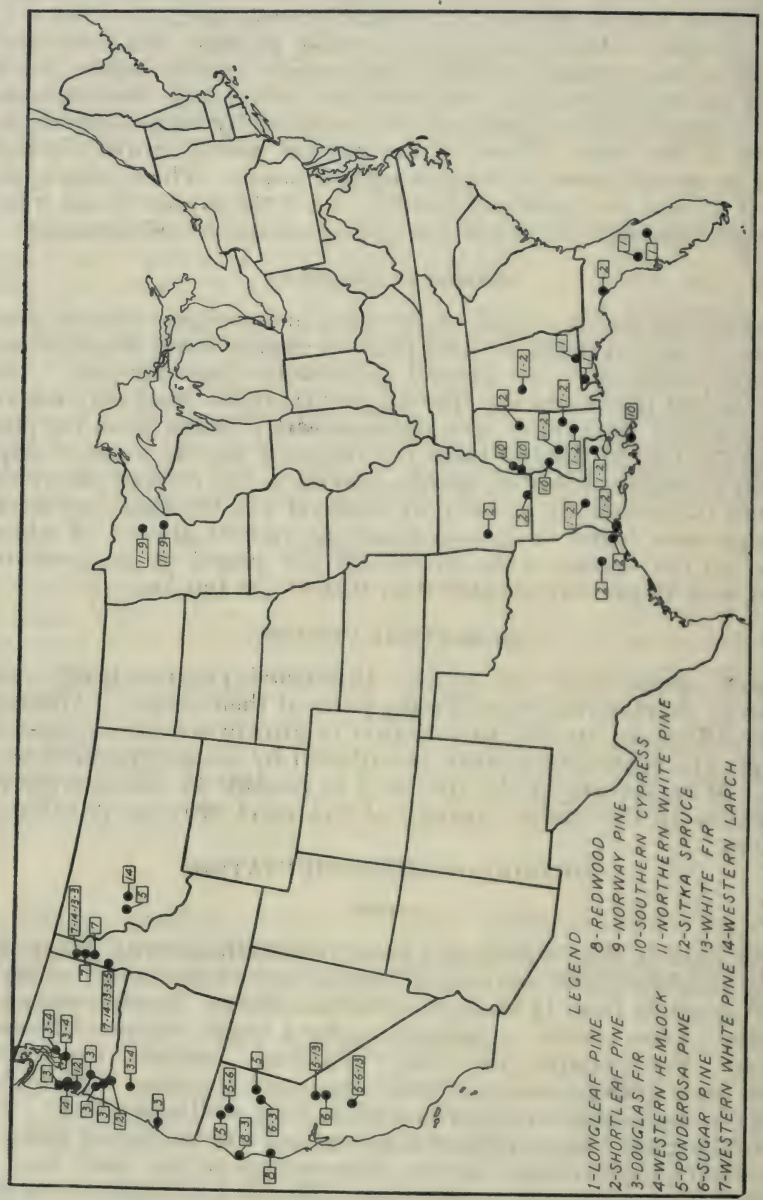


FIGURE 2.—Location of sawmills visited and the kinds of lumber studied at each

TABLE 1.—*The number and character of the specimens from which specific-gravity determinations were made*

Kind of lumber	Species	State where grown	Sawmills at which specimens were collected	Specimens							
				Heartwood, lumber grade				Sapwood, lumber grade			
				Select [1]	Common [2]	Flooring [3]	No designation	Select [1]	Common [2]	Flooring [3]	No designation
			Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
Longleaf pine [4]	*Pinus palustris*	Alabama	2	9	261	398		122	191	335	
		Mississippi	3	79	357	174		206	199	299	
		Louisiana	3	87	395	295		187	289	318	
		Florida	3				651				545
Total			11	175	1,013	867	651	515	679	952	545
Shortleaf pine [4]	*Pinus echinata* and *P. taeda*	Arkansas	2	82	169	198		356	321	327	
		Alabama	1		5			26	74	23	
		Mississippi	4	14	17	37		291	640	235	
		Florida	1				39				167
		Louisiana	3	5	19	85		14	50	151	
		Texas	2	47	83	35		114	441	285	
Total			13	148	293	355	39	801	1,526	1,021	167
Southern cypress	*Taxodium distichum*	Mississippi	3	121			9	25			11
		Louisiana	1	142	57			11	1		
Total			4	263	57		9	36	1		11
Douglas fir	*Pseudotsuga taxifolia*	Washington	4	598	476			228	54		
		Oregon	4	886	400			101	21		
		California	2	204	219			111	82		
		Idaho	2	52	124			3	9		
Total			12	1,740	1,219			443	166		
Western hemlock	*Tsuga heterophylla*	Washington	3	524	173			219	99		
		Oregon	1	201	134				9		
Total			4	725	307			219	108		

[1] Better than No. 1 Common.
[2] No. 1 Common and below.
[3] Distinction made in southern yellow pine only.
[4] Commercial designation.

TABLE 1.—*The number and character of the specimens from which specific-gravity determinations were made*—Continued

Kind of lumber	Species	State where grown	Sawmills at which specimens were collected	Specimens							
				Heartwood, lumber grade				Sapwood, lumber grade			
				Select	Common	Flooring	No designation	Select	Common	Flooring	No designation
			Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
Sitka spruce	*Picea sitchensis*	Washington	1	266	70			5			
		Oregon	1	108	162			15	32		
Total			2	374	232			20	32		
Ponderosa pine [5]	*Pinus ponderosa*	California	5	403	252			549	125		
		Idaho	1	18	94			41	156		
		Montana	1	6	109			20	103		
Total			7	427	455			610	384		
Sugar pine	*Pinus lambertiana*	California	4	381	103			381	100		
Western white pine	*Pinus monticola*	Idaho	4	252	472			126	329		
Redwood	*Sequoia sempervirens*	California	2	585				[6] 10			
White fir [4]	*Abies concolor* and *A. grandis*	Idaho	2		598						
		California	2	9	580						
Total			4	[7] 9	[7] 1,178						
Western larch	*Larix occidentalis*	Idaho	2	460	172			83	2		
		Montana	1		103						
Total			3	460	275			83	2		
Northern white pine	*Pinus strobus*	Minnesota	2	110	153			114	9		
Norway pine	*Pinus resinosa*	do	2	19	49			29	24		

[4] Commercial designation.
[5] Formerly called western yellow pine.
[6] Sapwood samples of redwood were not used in the final analysis on account of their small number.
[7] Separation of heartwood and sapwood impracticable.

COLLECTION OF SPECIMENS

Each specimen was cut approximately 2 feet from one end of a board or piece of lumber. Two crosscuts were made at this point, producing a section of the board about 1 inch in dimension along the grain. In cutting these sections serious defects, such as knots, were avoided. For each kind or item of lumber sampled, 40 or more sections were usually procured. About 300 sections from each species at each mill, representing the clear wood of all products of the log except large timbers, were obtained. The specimens that contained any appreciable quantity of compression wood were segregated from the rest. In addition, all specimens were subjected to a visual examination which resulted in the discarding of a few showing evidences of decay.

SPECIFIC-GRAVITY DETERMINATIONS

The specific-gravity values used for the comparison of species are based on the volume when green and the weight of the oven-dry wood. Since the specimens were cut from lumber that had been seasoned to some extent and consequently had shrunk, the first step was to bring them back to their green dimensions. This was accomplished by soaking them in cold water for four to five weeks. Previous experiments had demonstrated that specimens of this character would, for all practical purposes, recover their green dimensions on soaking in cold water for this length of time. The volumes of the soaked specimens were determined by displacement. In order to determine the weight of the wood when oven-dry, the specimens were placed in a drying oven and kept at a temperature of about 212° F. until a constant weight had been reached. Previous experiments had shown that leaching took place during the soaking period, but so little leaching occurred that it had no practical effect on the specific-gravity determinations.

DISCUSSION OF RESULTS

SPECIFIC-GRAVITY DATA

The specific-gravity data permit comparisons to be made in a number of ways. These fall naturally under two heads, comparison between different species and comparison within a species. The former consists of comparisons of all the lumber of a species, of heartwood alone, and of sapwood alone. Within a species comparisons are made between heartwood and sapwood, regions, mills, and lumber qualities.

In many of the softwoods studied, the average specific gravity of the heartwood was consistently greater than that of the sapwood. This is probably due largely to a greater percentage of extractive materials in the heartwood. In the consideration of specific-gravity values for those species having this difference between heartwood and sapwood, and possessing considerable sapwood, it is necessary to take into account the relative amount of heartwood and sapwood in those specimens upon which the values are based. A difference in specific gravity due to a difference in the proportion of heartwood to sapwood is a perfectly legitimate difference, but the method of collecting the test specimens gave no assurance that the percentage of heartwood and sapwood was fairly representative although it was probably

approximately so. In those species possessing considerable sapwood the percentage obtained in the specimens is affected considerably by the relative amounts of upper-grade and lower-grade lumber tested. The percentage of heartwood and sapwood is influenced greatly by the age of the timber, young timber possessing a larger percentage of sapwood than mature timber. Table 2 gives the average specific gravity for heartwood and for sapwood of each kind of lumber and also the percentage of heartwood in the specific-gravity specimens.

TABLE 2.—*Average specific gravity of heartwood and of sapwood for the various kinds of lumber studied, and the percentage of heartwood*

Kind of lumber	Average specific gravity		Comparative figure [1]		Heartwood [2]
	Heartwood	Sapwood	Heartwood	Sapwood	
			Points	*Points*	*Per cent*
Longleaf pine [3]	0.567	0.477	100	100	50
Shortleaf pine [3]	.510	.460	90	96	19
Western larch	.449	.430	79	90	90
Douglas fir	.440	.426	78	89	83
Western hemlock	.394	.395	69	83	76
Norway pine	.394	.376	69	79	56
Southern cypress	.388	.355	68	74	88
Ponderosa pine	.377	.359	66	75	47
Western white pine	.363	.360	64	75	61
Sitka spruce	.363	.333	64	70	92
Redwood	.358		63		98
Northern white pine	.348	.338	61	71	68
White fir [3]	.328	.328			(4)
Sugar pine	.326	.324	57	68	50

[1] The species of highest specific gravity has been designated 100 points, so that the comparison with other species can be made at a glance.
[2] These values are based on the proportion of heartwood specimens to the total number.
[3] Commercial designation.
[4] Heartwood and sapwood not distinguishable.

SPECIES AND REGIONAL COMPARISONS

Figures 3 to 8 show specific-gravity comparisons based on various factors. These figures show the average specific gravity and the variability in specific gravity. The average specific gravity is shown in each diagram by the vertical line that extends slightly above the top of the horizontal bar. The plain central area in each diagram shows points between which 50 per cent of the specific-gravity values fall, while the limits of the diagram show the approximate total range (99.95 per cent) of the values (*12*, *18*). In most of these charts the species are arranged in order of the magnitude of their average specific gravities.

The data shown in Figure 3 are based on tests on all of the specimens of each species. Each diagram for each species includes the specimens from different regions, different sawmills, heartwood, sapwood, and different lumber grades and sizes. Table 3 summarizes these data so that a comparison of species may readily be made, both with respect to the average specific gravity and range in specific gravity.

Figures 4 and 5 show that the average specific gravity of the heartwood of the different species varies more than the average specific gravity of the sapwood of the different species. For example, the difference between the average specific gravity of the heart-

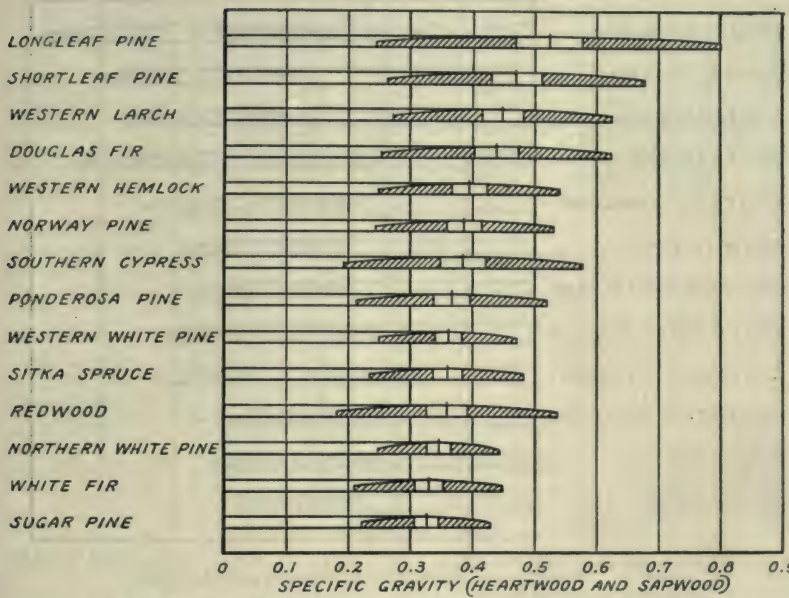


FIGURE 3.—Specific-gravity averages and ranges of the lumber of the various softwood species

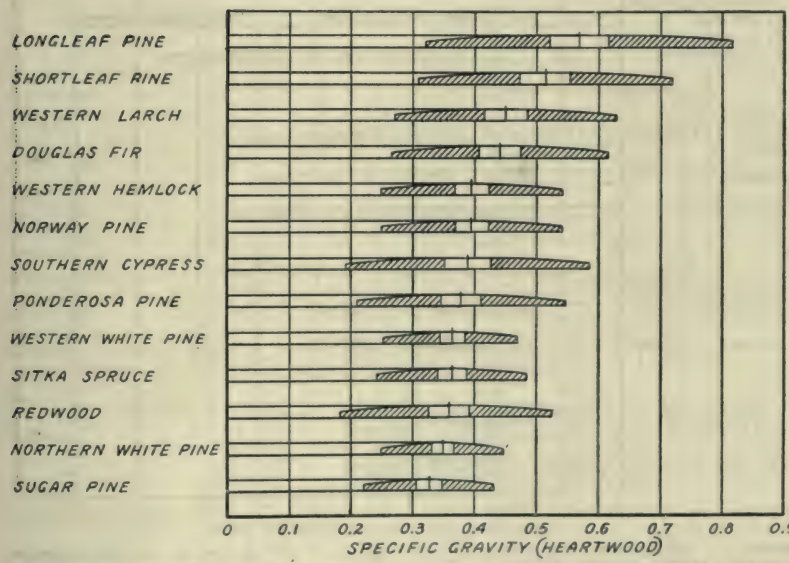


FIGURE 4.—Specific-gravity averages and ranges of the heartwood of the various softwood species

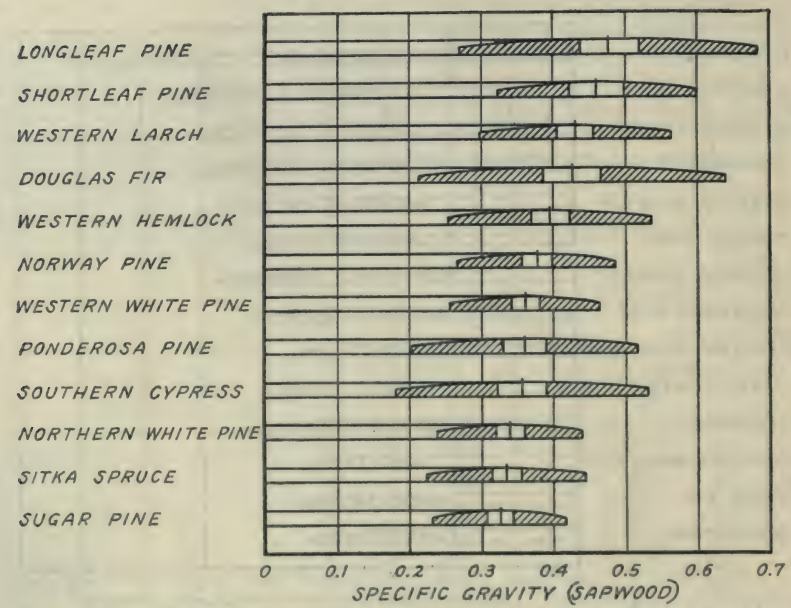


FIGURE 5.—Specific-gravity averages and ranges of the sapwood of the various softwood species

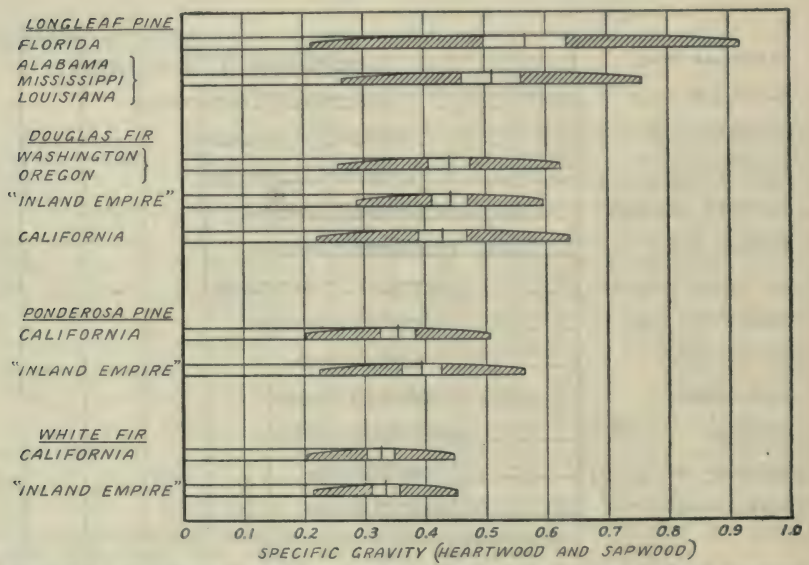


FIGURE 6.—Specific-gravity averages and ranges of the lumber of various softwood species from different regions. The "Inland Empire" region comprises northwestern Montana, Idaho north of the Salmon River, Washington east of the Cascade Mountains, and the northeastern tip of Oregon

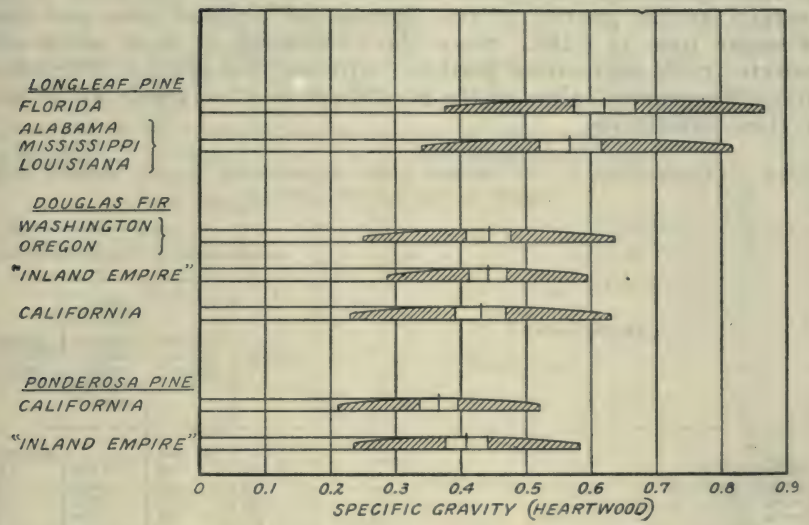


FIGURE 7.—Specific-gravity averages and ranges of the heartwood of several softwood species from different regions

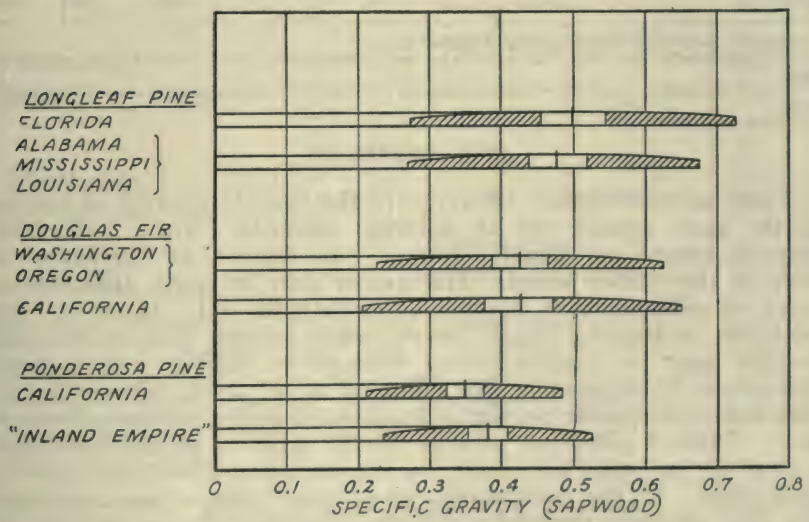


FIGURE 8.—Specific-gravity averages and ranges of the sapwood of several softwood species from different regions

wood of longleaf pine, which has the highest average specific gravity, and that of the heartwood of sugar pine, which has the lowest average specific gravity, is 0.241, whereas the difference between the average specific gravity of the sapwood of longleaf pine and that of sugar pine is 0.153. Since the heartwood in most softwoods contains more extractives than the sapwood, the greater differences in specific-gravity values of the heartwood may be largely attributed to these extractives.

TABLE 3.—*Comparison of the various kinds of softwood lumber studied with respect to the specific gravity*

Kind of lumber	Average value		Range in values	
	Actual	Comparative figure [1]	Difference between maximum and minimum [2]	Comparative figure [3]
		Per cent		*Per cent*
Longleaf pine [4]	0.522	100	0.556	100
Shortleaf pine [4]	.470	90	.416	82
Western larch	.448	86	.352	74
Douglas fir	.438	84	.368	79
Western hemlock	.394	75	.290	69
Norway pine	.386	74	.286	69
Southern cypress	.384	74	.384	93
Ponderosa pine	.366	70	.306	79
Western white pine	.361	69	.224	58
Sitka spruce	.359	69	.250	65
Redwood	.358	69	.354	93
Northern white pine	.345	66	.196	53
White fir [4]	.329	63	.240	68
Sugar pine	.325	62	.208	60

[1] Based on the average specific gravity of longleaf pine.
[2] The approximate total range, that is, 99.95 per cent of the specific-gravity values will fall within this range.
[3] Ratio of the range to the mean within each species, compared with that of longleaf pine, which is taken as 100.
[4] Commercial designation.

MILL COMPARISONS

There is considerable difference in the specific gravity of lumber of the same species cut at different sawmills. These differences may be caused by climatic factors, site factors, or characters or type of the timber stand. The timber may be quite different because of differences in exposure, rainfall, or soil. Moreover, one mill may be logging virgin timber, while another mill in the same locality may be logging young open-grown timber with a large percentage of sapwood. The effect of all of these various factors that influence specific gravity is manifested in the product of a sawmill. Table 4 gives the average specific gravity of the heartwood and of the sapwood separately for the lumber studied at the individual mills. If the heartwood and sapwood values were combined the mill averages would be influenced by the relative amounts of heartwood and sapwood in the specimens collected, which proportion might or might not be similar to that of the product of the mill as a whole.

TABLE 4.—*Average specific gravity of lumber, heartwood and sapwood separately, at the individual mills*[1]

Kind of lumber	State where grown	Average specific gravity	
		Heartwood	Sapwood
Longleaf pine[2]	Florida	0.611	0.511
		.636	.501
		.578	.483
	Mississippi	.535	.465
		.555	.476
		.544	.481
	Louisiana	.559	.459
		.573	.500
		.554	.468
	Alabama	.545	.465
		.527	.457
Weighted average		.567	.477
Western hemlock	Washington	.393	.383
		.403	.406
		.414	.414
	Oregon	.371	[3].370
Weighted average		.394	.395
Southern cypress	Louisiana	.400	.350
	Mississippi	.372	------
		.377	.360
		.365	.360
Weighted average		.388	.355
Sitka spruce	Washington	.366	.332
	Oregon	.359	.334
Weighted average		.363	.333
Western larch	Idaho	.475	.431
		.436	[3].416
	Montana	.415	------
Weighted average		.449	.430
Sugar pine	California	.332	.326
		.340	.334
		.326	[3].316
		.310	.312
Weighted average		.326	.324
Western white pine	Idaho	.349	.347
		.370	.362
		.363	.373
		.367	.348
Weighted average		.363	.360
Shortleaf and loblolly pine.[3]	Florida	[3].504	.473
	Mississippi	[3].509	.476
Shortleaf and loblolly pine.[3]	Mississippi	------	0.448
		0.504	.454
		[3].514	.447
	Arkansas	.494	.441
		.508	.455
	Texas	.521	.480
		[3].528	.498
	Louisiana	[3].490	.452
		[3].553	.475
		.533	.480
	Alabama	[3].413	.459
Weighted average		.510	.460
Norway pine	Minnesota	.364	[3].349
		.407	.378
Weighted average		.394	.376
Ponderosa pine	California	.409	.359
		.376	.353
		.347	.354
		.368	.350
		.349	.325
	Idaho	.405	.371
	Montana	.410	.388
Weighted average		.377	.359
Northern white pine	Minnesota	.345	.333
		.357	.339
Weighted average		.348	.338
Douglas fir	Washington	.435	[3].450
		.440	.443
		.450	.418
		.450	.425
	Oregon	.425	.396
		.448	.417
		.425	[3].395
		.474	[3].418
	Idaho	.464	[3].442
		.431	[3].451
	California	.396	.379
		.467	.464
Weighted average		.440	.426
Redwood	California	.361	------
		.356	------
Weighted average		.358	------

[1] Separation of heartwood and sapwood in white fir is impracticable. The average specific gravity of the white fir from two California mills was 0.326 and 0.324 and from two "Inland Empire" mills, 0.325 and 0.338; the weighted average for the species was 0.328.
[2] Commercial designation.
[3] Inadequate number in sample.

COMPARISON OF AVERAGE SPECIFIC GRAVITY OF DIFFERENT QUALITIES OF LUMBER OF THE SAME SPECIES

The upper grades of lumber are obtained primarily from the outer portions of the logs, which contain the clear wood, and more from lower logs than from top logs. In most softwood species, the specific gravity of the sapwood is lower than that of the heartwood. In

mature or overmature timber the outer portion of the tree is made up of fine ringed wood that is often of low specific gravity. All of these things tend to cause a difference in specific gravity between upper and lower grade lumber within a species.

Table 5 gives a comparison of the average specific gravity of the upper and the lower grades of lumber studied. In some species the Select, or upper-grade, lumber is higher in average specific gravity than the Common, or lower-grade, lumber, whereas in others it is lower. The data are inadequate to offer an explanation of these differences.

TABLE 5.—*Average specific gravity and percentage of heartwood in Select and Common lumber* [1]

Kind of lumber	Select				Common			
	Heartwood	Sapwood	All wood	Heartwood	Heartwood	Sapwood	All wood	Heartwood
				Per cent [2]				*Per cent* [2]
Longleaf pine [3] [4]	0.559	0.466	0.499	33.5	0.540	0.469	0.508	57.8
Shortleaf pine [3] [5]	.515	.467	.474	15.5	.498	.448	.450	16.5
Southern cypress	.383	.351	.379	88.0	.406	.376	.401	84.5
Douglas fir (Washington and Oregon)	.449	.425	.444	82.0	.433	.424	.432	92.0
Western hemlock	.397	.401	.398	77.0	.383	.384	.383	72.0
Sitka spruce	.410	.337	.406	94.0	.364	.331	.360	88.0
Ponderosa pine (California)	.367	.347	.356	44.5	.365	.350	.358	53.5
Ponderosa pine ("Inland Empire")	.422	.393	.402	29.0	.406	.378	.390	43.5
Sugar pine	.318	.316	.317	49.0	.331	.325	.330	51.0
Western white pine	.375	.375	.375	66.5	.351	.351	.351	59.5
Western larch	.443	.405	.443	98.5	.451	.430	.448	87.5
Northern white pine	.357	.338	.346	43.0	.342	.332	.341	94.5
Norway pine	.426	.382	.399	39.5	.382	.369	.377	67.0

[1] Where specimens of one quality only were collected at a sawmill, they were not used in computing this table.

[2] Based on proportion of heartwood specimens to the total number.

[3] Commercial designation.

[4] The specific-gravity values of the heartwood, sapwood, and all wood, and percentage of heartwood of longleaf pine flooring were 0.559, 0.475, 0.513, and 47.7, respectively.

[5] The specific-gravity values of the heartwood, sapwood, and all wood, and percentage of heartwood of shortleaf pine flooring were 0.521, 0.470, 0.484, and 28.0, respectively.

COMPARISON OF PRESENT DATA WITH PREVIOUSLY PUBLISHED DATA

Many data have been published previously on the specific gravity of various species. The chief difference between the previously published data and those presented in this bulletin is that the present data were obtained by a different method of sampling. Table 6 affords a comparison of the present data, based on specimens obtained from lumber, with that based on specimens obtained from the top of the butt log of selected trees (*9*). For most of the species the data based on the lumber designation represent wood from a greater number of trees more widely distributed over the geographical range of the species than do the botanical data. There are some relatively small differences between these sets of data, which is not surprising considering the different method of collecting the specific-gravity specimens and differences in the method of making the tests. Such small differences may or may not be important, depending on the use to which the wood is put.

TABLE 6.—*Comparison of lumber data with botanical data*

Kind of lumber	Lumber data		Botanical data [1]		
	Average specific gravity	Specimens	Average specific gravity	Trees tested	Specimens
		Number		*Number*	*Number*
Longleaf pine	[2] 0.52	5,397	0.55	34	806
Loblolly pine	[2] .47	4,350	.50	10	1,190
Shortleaf pine			.49	12	
Western larch	.45	820	.48	13	214
Douglas fir (Washington and Oregon)	.44	2,764	.45	34	1,029
Douglas fir ("Inland Empire")	.44	188	.41	10	113
Western hemlock	.39	1,359	.38	18	689
Norway pine	.39	121	.44	5	126
Southern cypress	.38	377	.42	26	479
Ponderosa pine	.37	1,876	.38	31	579
Western white pine	.36	1,179	.36	14	211
Sitka spruce	.36	658	.37	25	1,392
Redwood	.36	585	.39	16	564
Northern white pine	.35	386	.34	18	290
White fir	[2] .33	1,187	.35	45	278
Sugar pine	.33	965	.35	9	191

[1] Markwardt, L. J. (*9*). [2] Species unknown, based on commercial designation.

RELATION BETWEEN SPECIFIC GRAVITY AND VARIOUS PROPERTIES

The specific gravity of wood through its effect on the properties has to a large degree controlled the uses to which wood has been put. There are other properties besides specific gravity that determine the suitability of a wood for specific purposes but specific gravity is a very important one. Considerable information concerning the effect of specific gravity on some properties exists, but for many others it is lacking.

MECHANICAL PROPERTIES

The mechanical properties of wood are related to its specific gravity and increase with an increase in specific gravity (*9*, *10*). For uses where it is important that the wood be hard, stiff, or resistant to breaking it is important that the specific gravity be high. In a number of softwood species the pieces of wood of high specific gravity may be separated from those of low specific gravity by a visual inspection. Where it is necessary to select wood for maximum-strength properties it is usually sufficient merely to discard those pieces showing a small percentage of summer wood. (P. 2.) Figure 9 shows the relation of specific gravity to the modulus of rupture for 114 species of hardwoods and 48 species of softwoods (*8*). The correlation within a species of specific gravity and modulus of rupture is closer than among species.

In general, wood of high specific gravity will resist wearing better than wood of low specific gravity; therefore dense wood is the more suitable for flooring. Species in which there is a marked difference between the heavy summer wood and the light spring wood usually possess a greater tendency to sliver than do other species. Edge-grained material wears more uniformly than flat-grained material, especially in woods with a great contrast between the summer wood and spring wood.

The nail-holding properties of wood are closely related to its specific gravity, the denser the wood the greater its nail-holding power (*15*).

Although there is relatively little information on nail splitting, such experiments as have been made indicate that the denser woods have a greater tendency to split in nailing. It is also general opinion

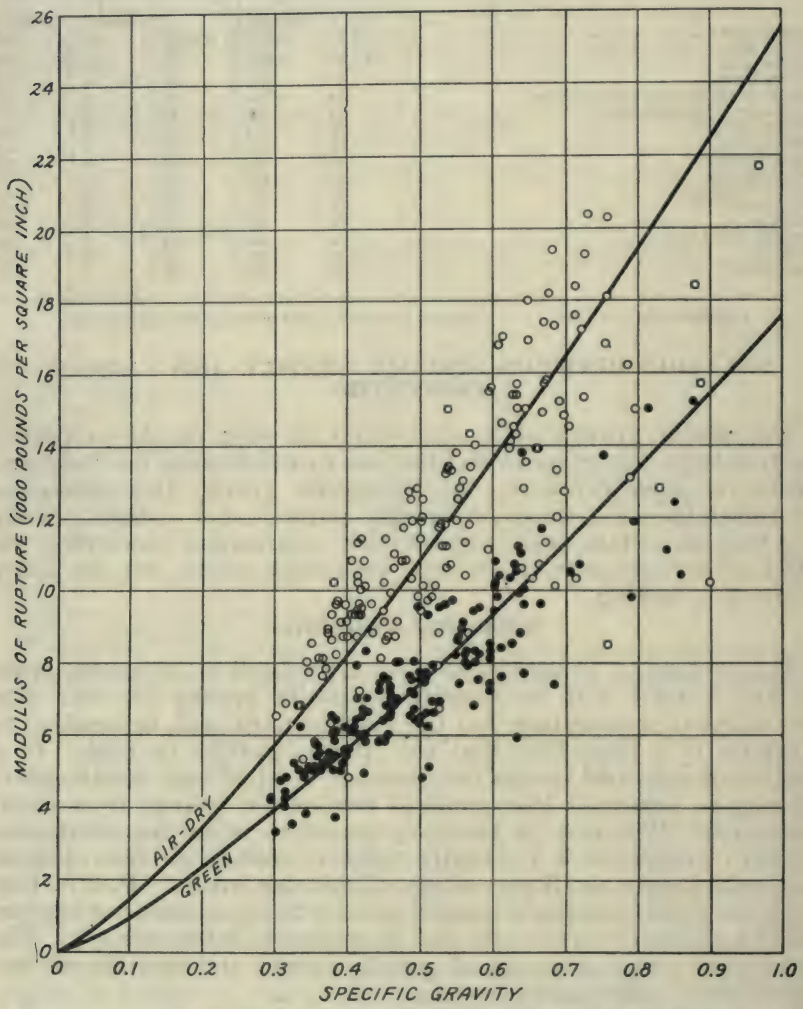


FIGURE 9.—Relation of modulus of rupture to specific gravity in hardwoods of 114 species and softwoods of 48 species, both green and air dry

that of two woods with similar specific gravities the one having the greater contrast between the summer wood and the spring wood has a greater tendency to split (*4*).

DRYING RATE

As far as is known, no information exists concerning the effect of specific gravity alone on the rate of percentage moisture loss from

wood. The differences in the drying rates of the various softwood species are probably due to factors other than specific gravity. A dense wood loses more moisture, in an absolute sense, than a light wood in losing the same percentage of moisture, since in the dense wood each percentage of moisture content represents a greater amount of moisture. If a piece of wood is heavy because it has a large amount of extractive material the drying will probably be hindered somewhat by the presence of the extractives.

EQUILIBRIUM MOISTURE CONTENT

For practical purposes it has always been maintained that wood, regardless of the species, heartwood or sapwood, specific gravity, and the like, comes to a constant moisture-content condition when exposed to a given temperature and relative humidity for a prolonged period. Indications that there are some deviations from this general rule have been found, especially with respect to the influence of different quantities of extractives. Experiments with the heartwood of longleaf and of shortleaf pine indicate that the moisture-content equilibrium values for resinous woods are lower than for wood that is not so resinous (*19*).

SHRINKAGE

In general, woods of high specific gravity shrink in volume more than woods of low specific gravity, although this relation is subject to considerable irregularity both among different species and among individual pieces of the same species. When the shrinkage of wood is resolved into its three components—tangential, radial, and longitudinal—the relationship with specific gravity becomes more complex. In the plane perpendicular to the axis of the tree, dense wood shrinks more than light wood; in the plane parallel to the axis of the tree dense wood shrinks less than light wood. Compression wood, which is very dense abnormal wood, has a much greater shrinkage in a longitudinal direction than normal wood, and a smaller shrinkage in the other two directions than normal wood. Various investigators (*3*, *13*) have found that thick-walled cells shrink more tangentially and radially than do thin-walled cells. This would explain why dense woods, which possess a large proportion of thick-walled cells, ordinarily shrink more than light woods.

WOODWORKING PROPERTIES

Specific gravity plays an important part in the ease with which a wood may be cut, planed, shaped, or otherwise worked. Light woods are more easily worked than heavy woods. Other properties besides specific gravity also affect the workability of wood. A light wood with lack of contrast between summer wood and spring wood works more easily than one with great contrast between summer wood and spring wood. Straightness of grain is also necessary if wood is to be easily worked.

Among the softwood species dealt with in this bulletin there is a slight contrast between the summer wood and spring wood in northern white pine, sugar pine, and western white pine; in Sitka spruce, western hemlock, white fir, redwood, and southern cypress there is a moderate contrast between the summer wood and spring

wood; in ponderosa pine there is a pronounced contrast between spring wood and summer wood, but the width of the summer wood varies greatly; and in Norway pine, Douglas fir, western larch, shortleaf pine, and longleaf pine there is a great contrast between the summer wood and spring wood.

PAINTING PROPERTIES

As a general rule woods of low specific gravity are more satisfactory for painting purposes than woods of high specific gravity (*2*). Besides specific gravity, however, the width of the bands of dense summer wood is important. Two woods might have the same average specific gravity, but the one of faster growth would have wider bands of summer wood and would therefore be less satisfactory for painting. In exterior painting the paint fails first on the summer wood of wide-ringed wood, especially on the tangential faces where there are larger areas of summer wood than on the radial ones. For interior painting a light wood with slight contrast between the summer wood and spring wood is preferable to a wood with marked contrast, because the grain in the latter will often show through an enameled surface.

GLUING PROPERTIES

In general specific gravity affects the gluing properties of softwoods, but gluing of wood is such a complicated matter that it is impossible to state any simple relation (*14*). A light wood with slight contrast between summer wood and spring wood is easier to glue than a heavy wood with great contrast between summer wood and spring wood because it is difficult to make the glue adhere satisfactorily to the hard, dense summer-wood bands. The denser woods are preferred for strong glued joints because in joints made under proper gluing conditions failure is usually in the wood and not in the glue; consequently the denser woods make the strongest glued joints. It is possible, however, under proper gluing conditions to make joints in practically all softwoods as strong as the wood itself. Special care must be taken with the dense woods.

RAISED GRAIN

Raised grain results in the corrugated appearance of the surfaces of lumber and is caused by the summer wood either projecting above or being depressed below the level of the spring wood. This may be brought about either by the pounding of the harder summer wood into the softer spring wood in the process of surfacing in the manufacture of lumber or by the differential shrinkage of the spring wood and summer wood (*6*). Raised grain usually occurs where there is a marked contrast between summer wood and spring wood, but it is not influenced by the specific gravity of the wood as a whole.

SHIPPING WEIGHTS

The weight of a given quantity of lumber depends on the amount of wood substance plus extractives and the amount of water present. At a definite moisture content the lumber that has the highest specific-gravity value will weigh the most. Another factor that contributes to this difference in weight is the fact that a certain percent-

age of moisture in a heavy wood represents more absolute water than the same percentage in a lighter wood. Table 7 gives the actual weight per thousand board feet as well as that based on one standard commercial size of the softwood lumber studied. To obtain the weight of any pattern or size of lumber at 12 per cent moisture content it is necessary only to find the ratio of the actual cross section of the lumber to the cross section on which the lumber scale is based, and multiply the values in the next-to-the-last column of Table 7 by this ratio. For the 1 by 8 inch boards given in Table 7 this ratio is 0.732, determined in the following manner:

$$\frac{\frac{25}{32}\times 7\frac{1}{2}}{1\times 8}=\frac{0.781\times 7.5}{1\times 8}=\frac{5.85}{8.0}=0.732$$

where $\frac{25}{32}$ by $7\frac{1}{2}$ inches are the actual cross-sectional dimensions and 1 by 8 inches are the cross-sectional dimensions on which the lumber scale is based.

TABLE 7.—*Weight of lumber in pounds per thousand board feet at 12 per cent moisture content*

Kind of lumber	Specific gravity	Calculated weight of dry wood in 1 cubic foot of green wood [1]	Calculated weight of dry wood in 1,000 board feet of green wood [2]	100 per cent minus shrinkage [3]	Weight of 1,000 board feet of dry wood at 12 per cent moisture content [4]	Values in preceding column plus 12 per cent for the weight of water [5]	Calculated weight of 1,000 board feet of 1 by 8 inch lumber [6]
		Pounds	*Pounds*	*Per cent*	*Pounds*	*Pounds*	*Pounds*
Longleaf pine [7]	0.522	32.57	2,714	93.5	2,903	3,251	2,380
Shortleaf pine [7]	.470	29.33	2,444	93.5	2,614	2,928	2,143
Western larch	.448	27.96	2,330	94.0	2,479	2,776	2,032
Douglas fir	.438	27.33	2,277	94.0	2,422	2,713	1,986
Western hemlock	.394	24.59	2,049	94.0	2,180	2,442	1,788
Norway pine	.386	24.09	2,007	94.0	2,135	2,391	1,750
Southern cypress	.384	23.96	1,997	95.0	2,102	2,354	1,723
Ponderosa pine	.366	22.84	1,903	95.0	2,003	2,243	1,642
Western white pine	.361	22.53	1,877	94.5	1,986	2,224	1,628
Sitka spruce	.359	22.40	1,867	94.0	1,986	2,224	1,628
Redwood	.358	22.34	1,862	96.5	1,930	2,162	1,583
Northern white pine	.345	21.53	1,794	96.0	1,869	2,093	1,532
White fir [7]	.329	20.53	1,711	95.0	1,801	2,017	1,476
Sugar pine	.325	20.28	1,690	96.0	1,760	1,971	1,443

[1] Specific gravity times 62.4.
[2] Value in preceding column times 83.3. There are 83.3 cubic feet in a thousand 1 by 1 by 12 inch board feet.
[3] One hundred per cent minus approximately one-half of the total volumetric shrinkage.
[4] Weight of wood per thousand board feet divided by 100 minus percentage shrinkage.
[5] Weight of wood per thousand board feet divided by 100 minus percentage shrinkage, plus weight of water.
[6] Values in preceding column multiplied by 0.732, which is the ratio of the actual cross-sectional area of the boards to the cross-sectional area on which the lumber scale is based.
[7] Commercial designation.

The figures in Table 7 are based on the average specific-gravity values obtained in the present study. Because there is considerable variation in specific gravity among pieces of the same species, the weight of any particular thousand board feet of lumber at a moisture content of 12 per cent will seldom be the same as that given in Table 7 but, in the absence of actual weighing, will be a close approximation of the weight and may be used for most practical purposes.

TREATING PROPERTIES

In the treating of wood for preservative purposes the effect of specific gravity, if any, is completely obscured by other more important factors.

FUEL VALUE

The heating value of a given volume of dry wood is in direct relation to its specific gravity (*5*). A given weight of one wood has approximately the same value as a like weight of another wood, although the presence of certain extractives alters this relation by increasing the fuel value.

HEAT CONDUCTIVITY

Wood depends for its heat-insulating properties on its cellular structure (*1*, *16*). Wood is composed of small cells which, when dry, contain air in the cavities. In general the efficiency of an insulating material depends on the percentage of air space and the distribution of this air space. One large air space is not nearly so effective as a large number of small spaces. Wood has naturally a very advantageous distribution of the air space. The greater the percentage of air space, provided it is advantageously distributed, the better the insulation. Light wood contains a greater proportion of air space than dense wood; therefore, the insulating property of wood varies inversely as its specific gravity.

PULP YIELD

When calculating the yield of pulp from a given volume of wood, such as a cord, the yield is related to the specific gravity of the wood (*17*). Extractive materials, although contributing to the specific gravity of wood, contribute nothing to the pulp yield, as this is made up chiefly of the stable cellulose originally in the wood.

SUMMARY

In classifying softwood lumber with respect to specific gravity three things should be considered: (1) The average specific gravity, (2) the lack of uniformity among individual pieces, and (3) the contrast between the spring wood and the summer wood. Longleaf pine, shortleaf pine, western larch, and Douglas fir are heavy woods; western hemlock, Norway pine, southern cypress, ponderosa pine, western white pine, Sitka spruce, and redwood are moderately heavy woods; and northern white pine, white fir, and sugar pine are light woods. Longleaf pine, southern cypress, redwood, shortleaf pine, Douglas fir, ponderosa pine, and western larch have a great range in specific gravity; western hemlock and Norway pine have a moderate range; and white fir, Sitka spruce, sugar pine, western white pine, and northern white pine have a small range. In longleaf pine, shortleaf pine, western larch, Douglas fir, and Norway pine there is a strong contrast between the spring wood and the summer wood; in ponderosa pine also there is a pronounced contrast between spring wood and summer wood, but the width of the summer wood varies greatly; in southern cypress, Sitka spruce, western hemlock, white fir, and redwood there is a moderate contrast; in western white pine,

northern white pine, and sugar pine there is only a slight contrast between the spring wood and the summer wood.

The range in specific gravity is wide in different kinds of softwood lumber and also in individual pieces of lumber of the same species. In most softwood species an appreciable difference is found between the specific gravity of heartwood and of sapwood.

As an index to the usefulness or suitability of lumber for definite purposes, not only is it important to know the average specific gravity but also the range in specific gravity. With such knowledge it is often possible to select individual pieces of a weak species exceeding in strength the average of a stronger one, and to segregate the lumber of a species into specific-gravity classes, so that each class may be directed to the uses for which it is best suited. It is also important to take into consideration the contrast between the summer wood and the spring wood.

LITERATURE CITED

(1) Austin, L. W., and Eastman, C. W.
1902. on the relation between heat conductivity and density in some of the common woods. Wis. Acad. Sci., Arts, and Letters, Trans. 13: [539]–542, illus.

(2) Browne, F. L.
1930. how properties of wood determine the service given by exterior paint coatings. Amer. Paint Jour. 14(25): 22, 24, 26, 28, 68, 70, 72, 74, 76, 78, illus.

(3) Clarke, S. H.
1930. the differential shrinkage of wood. Forestry: Jour. Soc. Foresters Gt. Brit. 4: [93]–104, illus.

(4) Johnson, R. P. A.
1929. properties of western hemlock and their relation to uses of the wood. U. S. Dept. Agr. Tech. Bul. 139, 62 p., illus.

(5) ——— Kittredge, J., Jr., and Schmitz, H.
1930. aspen: availability, properties, and utilization. Minn. Agr. Exp. Sta. Tech. Bul. 70, 72 p., illus.

(6) Koehler, A.
1930. causes and prevention of raised grain. Timberman 31(4): 162, 164, 166, illus.

(7) Luxford, R. F., and Markwardt, L. J.
1932. the strength and related properties of redwood. U. S. Dept. Agr. Tech. Bul. 305, 48 p., illus.

(8) Markwardt, L. J.
1930. aircraft woods: their properties, selection, and characteristics. Natl. Advisory Com. Aeronaut. Rpt. 354, 34 p., illus.

(9) ———
1930. comparative strength properties of wood grown in the united states. U. S. Dept. Agr. Tech. Bul. 158, 39 p.

(10) Newlin, J. A., and Wilson, T. R. C.
1917. mechanical properties of woods grown in the united states. U. S. Dept. Agr. Bul. 556, 47 p., illus.

(11) Paul, B. H.
1930. the application of silviculture in controlling the specific gravity of wood. U. S. Dept. Agr. Tech. Bul. 168, 20 p., illus.

(12) Rietz, H. L., Carver, H. C., Crathorne, A. R., Crum, W. L., Glover, J. W., Huntington, E. V., Kelley, T. L., Persons, W. M., and Young, A. A.
1924. handbook of mathematical statistics. 221 p., illus. Boston, New York, [etc.]

(13) Roth, F.
1895. timber: an elementary discussion of the characteristics and properties of wood. U. S. Dept. Agr., Forestry Bul. 10, 88 p., illus.

(14) Truax, T. R.
1929. the gluing of wood. U. S. Dept. Agr. Dept. Bul. 1500, 78 p., illus.

(15) UNITED STATES DEPARTMENT OF AGRICULTURE.
1931. NAIL-HOLDING POWER OF AMERICAN WOODS. U. S. Dept. Agr., Forest Prod. Lab. Tech. Note 236, 4 p.
(16) VAN DUSEN, M. S.
1920. THE THERMAL CONDUCTIVITY OF HEAT INSULATORS. Refrig. Engin. 7: 202–231, illus. (Also published in Jour. Amer. Soc. Heating and Ventilating Engin. 26: 625–656, illus.)
(17) WELLS, S. D., and RUE, J. D.
1927. THE SUITABILITY OF AMERICAN WOODS FOR PAPER PULP. U. S. Dept. Agr. Dept. Bul. 1485, 102 p., illus.
(18) YULE, G. U.
1924. AN INTRODUCTION TO THE THEORY OF STATISTICS. Ed. 7, 415 p., illus. London.
(19) ZELLER, S. M.
1920. HUMIDITY IN RELATION TO MOISTURE IMBIBITION BY WOOD AND TO SPORE GERMINATION ON WOOD. Ann. Missouri Bot. Gard. 7: 51–74, illus.

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - Price 5 cents

TECHNICAL BULLETIN No. 342 JANUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

CAUSES OF BRASHNESS IN WOOD

By ARTHUR KOEHLER [1]

Principal Xylotomist, Forest Products Laboratory,[2] Branch of Research, Forest Service

CONTENTS

	Page
Introduction	1
Brashness and toughness	1
Properties of brash wood	4
Accidental factors affecting type of failure and toughness of wood	8
Causes of brashness investigated	10
Species differences	10
Environmental factors	10
Width of growth rings	10
Percentage of summer wood	12
Sapwood as compared with heartwood	13
Cellular structure of wood low in density for its species	14
Causes of brashness investigated—Con.	
Cellular structure of wood of medium and of high density for its species	18
Existing compression failures	27
Cross grain	31
Height in tree	31
Distance and direction from center of tree	32
Ratio of tensile ot compressive strength	32
High temperature	33
Chemical composition	35
Decay	36
Summary	37
Literature cited	38

INTRODUCTION

Wood, like other structural materials, contains visible defects and other abnormalties of structure that necessitate careful inspection of the material. One of these abnormalities is a condition known as brashness. The purpose of this bulletin is to present a discussion of brashness, including chiefly its known causes and methods for recognizing brash pieces. The elimination of brash wood from structures in which it might cause loss of life or property is essential for satisfactory service and efficient use of wood. A knowledge of the factors that cause brashness may also be valuable in preventing wood from becoming brash during its growth or subsequent thereto.

BRASHNESS AND TOUGHNESS

In popular usage the term brash generally means the characteristic that causes a piece of wood to break abruptly across the grain, with relatively low resistance to such breaking. Occasionally the

[1] Acknowledgment is made to B. S. Dain, R. W. Smith, and J. L. Bienfait, formerly of the Forest Products Laboratory staff, and M. Y. Pillow, of the present staff, for assistance in carrying on the anatomical investigations discussed in this bulletin; to the Division of Forest Pathology, Bureau of Plant Industry, for examining numerous specimens for the presence of decay; and to J. A. Newlin, R. F. Luxford, and others of the section of timber mechanics of the Forest Products Laboratory for supplying most of the mechanical data on which this bulletin is based and for making helpful suggestions during its preparation.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

148936°—33——1

term is used for wood that shows brittleness in fracture, without reference to its strength, or, very loosely and probably incorrectly, for wood that is relatively weak in bending, without reference to the manner in which it breaks. Experience has taught, however, that brittleness in fracture and weakness usually go together, and the two are commonly associated in thought even when only one is mentioned. Ordinarily the term applies to wood bent along the grain, although it is occasionally applied loosely to wood bent across the grain, such as cupped lumber that splits easily in straightening.

Speaking technically, brash wood breaks suddenly and completely across the grain with brittleness in fracture and with a compara-

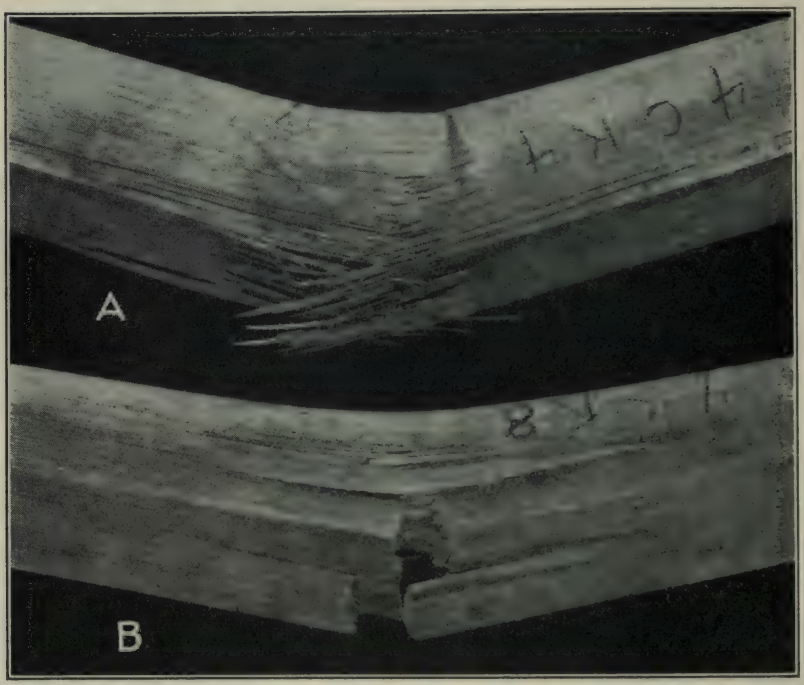


FIGURE 1.—Typical fractures in hickory tested under impact bending: A, Normal wood after a 50-inch drop of the hammer; B, brash wood after an 18-inch drop

tively small deflection. Consequently it absorbs relatively little energy in bending. Wood that is characterized as tough, on the other hand, breaks gradually, with continued splintering, and only after comparatively large deflection in bending has occurred. Consequently such wood absorbs a large amount of energy before it breaks. Figure 1 shows characteristic fractures in tough and in brash hickory. Yet there is no sharp line of demarcation between brash and tough wood, all gradations between the two occurring within a species. The differences between extremes are greatest in woods that are commonly considered exceptionally tough, such as hickory and ash. Figures 2 and 3, which are discussed later in this bulletin, give more information about the specimens of Figure 1.

Ordinarily all species of wood splinter more or less on breaking, although there is considerable variation in that respect among

species. Within a species, however, some pieces of wood may be very brash. Brashness, therefore, is an extreme or abnormal con-

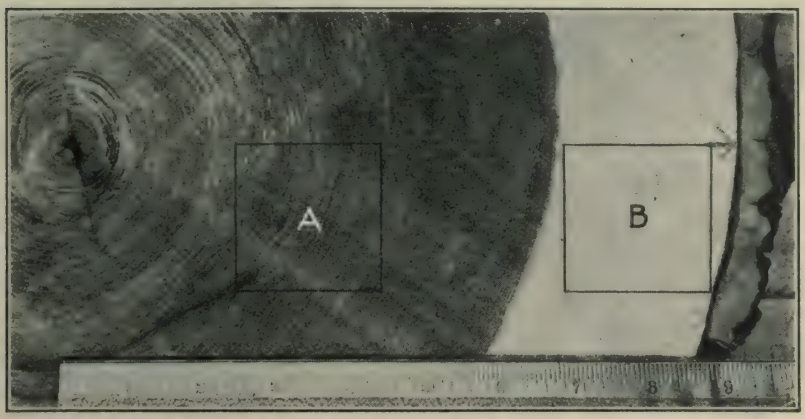


FIGURE 2.—Part of the end surface of a hickory log showing the portions from which the specimens of Figure 1 were taken; A, The normal wood; B, the brash wood

dition found only in a relatively small percentage of the wood of a species. As far as the absorption of energy is concerned, brashness is not comparable in different species of wood; for example, a brash piece of rock elm may absorb much more energy than a brash or even a tough piece of basswood.

Brashness in wood, incidentally, is synonymous in meaning with brittleness in other materials, such as glass, chalk, and cast iron, in so far as the abrupt type of failure and weakness in bending are concerned but, whereas brittleness may be a normal condition of such materials, brashness is an abnormal condition of wood. As used in this bulletin, brittleness refers primarily to the fracture and only by inference to the properties of the wood that cause such

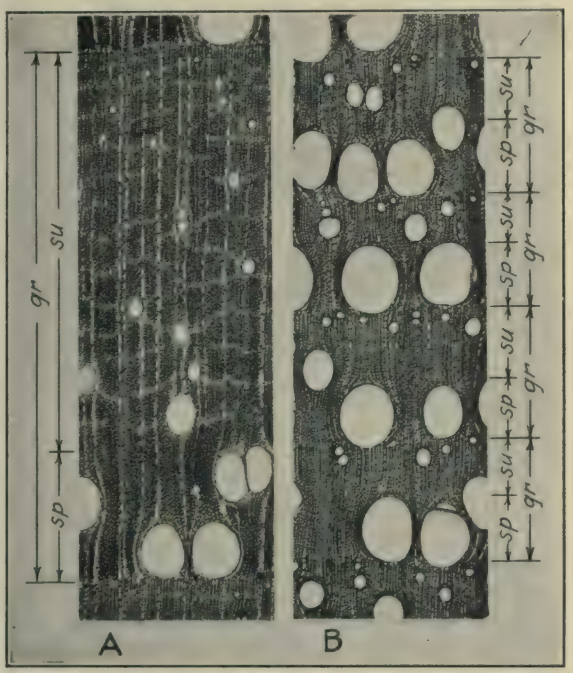


FIGURE 3.—Thin cross sections of representative portions of the hickory specimens in Figure 1; A, a wide growth ring having a high percentage of summer wood, from specimen A; B, narrow growth rings having small percentages of summer wood, from specimen B. *gr*, Growth ring; *sp*, spring wood; *su*, summer wood. × 20

a fracture, while brashness definitely includes degree of toughness as well as type of fracture. Brittleness, then, is less restricted in its meaning than brashness. Further, as used here, brashness refers primarily to a comparison made within a species rather than between species.

PROPERTIES OF BRASH WOOD

Table 1 shows the differences in certain mechanical properties of brash and of tough white ash and Sitka spruce tested in static bending. All ash specimens classified as brash broke abruptly across the grain, and all classified as tough broke in long slivers, producing extremely splintered fractures. In the spruce the difference in the appearance of the fractures of brash and of tough specimens was not so marked. This table indicates that the largest difference in the properties of the brash and the tough wood occurred in work to maximum load. In the ash the next largest difference was in deflection at maximum load, and then in fiber stress at maximum load (modulus of rupture). The relatively small deflection and the low maximum strength of the brash specimens account for the small amount of work absorbed in bending them to the maximum load they could carry. Far less difference in the mechanical properties of the brash and the tough ash and spruce occurred in modulus of elasticity, fiber stress at elastic limit, work to elastic limit, and, for the ash, deflection at elastic limit, showing thereby that the large differences between the brash and the tough woods occurred after their elastic limits had been passed. Figure 4 shows graphically the difference in these properties in the brash and the tough ash tested.

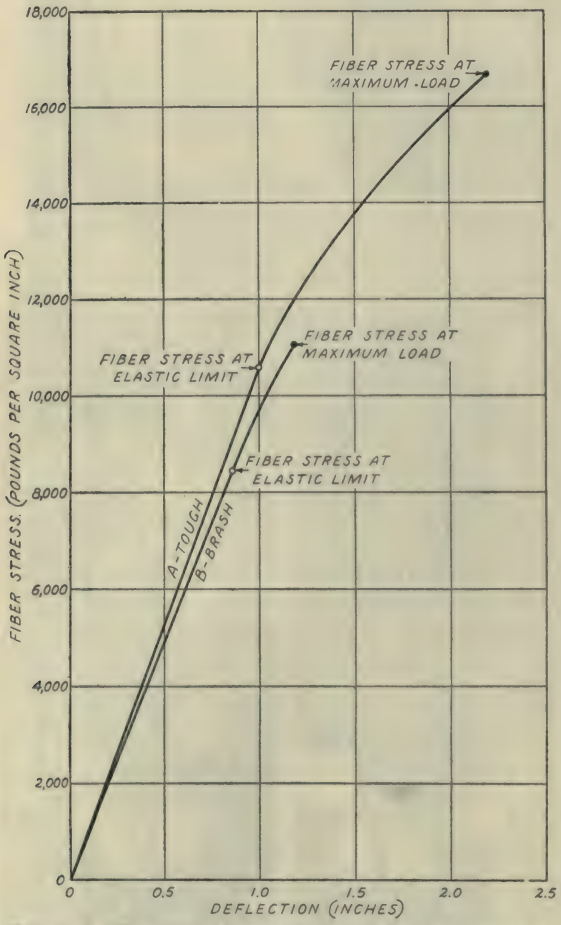


FIGURE 4.—Variation of average stress with deflections for the white ash specimens of Table 1

The brash and the tough specimens of each species in Table 1 were selected so as to come to about the same average in specific

gravity, in order to make the values for the same property and between properties more directly comparable. If brash and tough specimens had been selected at random for these species, the brash specimens would undoubtedly have ranked still lower in all mechanical properties because the brash group would then have contained a larger percentage of specimens low in weight and therefore weaker in all respects than the tough group, since wood light in weight for a species is usually brash. Figures 5 and 6 show that all the light-

TABLE 1.—*Average values of mechanical properties of brash and of tough, small specimens of clear wood tested in static bending*

Species of wood	Classification of specimens	Specimens tested	Specific gravity [1]	Fiber stress at— Elastic limit	Fiber stress at— Maximum load	Modulus of elasticity	Deflection at— Elastic limit	Deflection at— Maximum load	Work to— Elastic limit	Work to— Maximum load	Moisture content
		No.		*Lbs. per sq. in.*	*Lbs. per sq. in.*	*1,000 lbs. per sq. in.*	*In.*	*In.*	*In.-lbs. per cu. in.*	*In.-lbs. per cu. in.*	*Per cent*
Commercial white ash	Brash	15	0.562	8,440	11,180	1,910	0.86	1.19	3.50	7.1	6.9
	Tough	20	.566	10,660	16,650	2,050	.99	2.17	5.18	22.1	6.7
Percentage relation of brash to tough			99.3	79.2	67.1	93.2	86.8	54.8	67.6	32.1	
Sitka spruce	Brash	17	.390	5,200	8,730	1,270			1.22	6.45	11.5
	Tough	14	.391	5,640	9,820	1,440			1.26	10.31	11.7
Percentage relation of brash to tough			99.8	92.2	88.9	88.2			96.8	62.6	

[1] Based on volume when air-dry and weight when oven-dry.

weight specimens of ash and of Sitka spruce tested for toughness were brash. Further, the moisture content was approximately the same for all specimens of each species, so that the moisture present affected equally the amount of bending and the type of fracture.

The term commercial in connection with some of the ash specimens and all of the oak means that the wood was designated as white ash and white oak when acquired, although it may have included or may have consisted entirely of botanical species other than true white ash (*Fraxinus americana* Linn.) and true white oak (*Quercus alba* Linn.), respectively. The various species constituting commercial white ash and commercial white oak can not be distinguished by means of the wood alone.

The strength values given in this bulletin are presented solely for the comparison of brash and of normal specimens, and do not necessarily represent typical values for any species. The Forest Products Laboratory has already published strength values, based on hundreds of tests, for design of structures and for comparison of species (*17*, *18*).[3] The values given here, averages of a smaller number of tests, should be used only for the special purpose for which they were obtained, the comparison of specimens, matched in some respects, of brash and of normal wood. Further, in the testing of successive groups of specimens different sizes of specimen and methods of loading were sometimes used, partly because of improvement in technic as the work progressed and also because

[3] Italic numbers in parentheses refer to Literature Cited, p. 38.

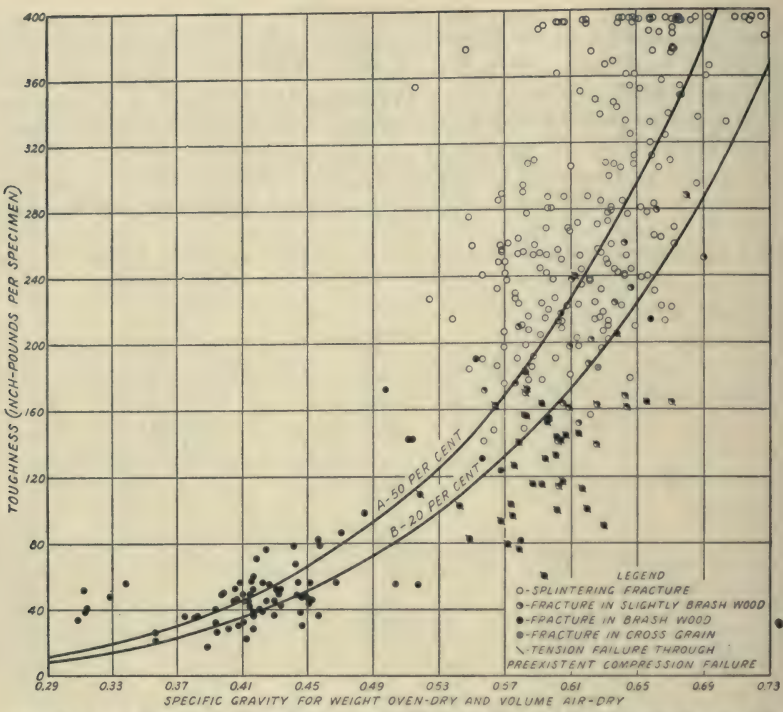

TOUGHNESS (INCH-POUNDS PER SPECIMEN)
SPECIFIC GRAVITY FOR WEIGHT OVEN-DRY AND VOLUME AIR-DRY
A-50 PER CENT
B-20 PER CENT
LEGEND
O-SPLINTERING FRACTURE
⊙-FRACTURE IN SLIGHTLY BRASH WOOD
●-FRACTURE IN BRASH WOOD
⊗-FRACTURE IN CROSS GRAIN
\-TENSION FAILURE THROUGH PREEXISTENT COMPRESSION FAILURE

FIGURE 5.—Relation to toughness to specific gravity of white ash loaded on the tangential surface: A, Median line—50 per cent of the points lie above the curve and 50 per cent below it; B, arbitrary low limit—20 per cent of the points lie below the curve

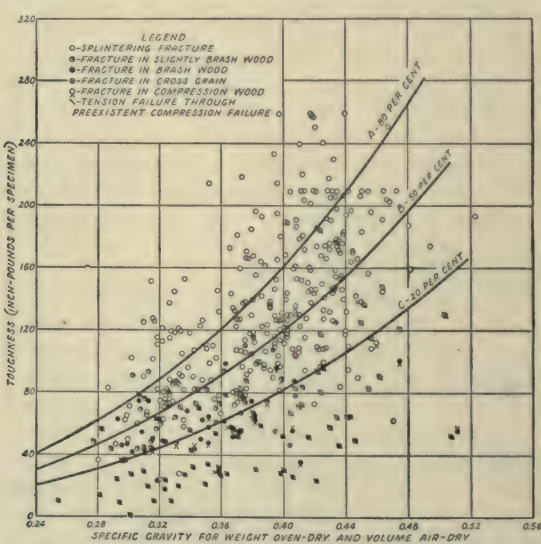


FIGURE 6.—Relation of toughness to specific gravity of Sitka spruce loaded on the tangential surface: A, Arbitrary high limit—20 per cent of the points lie above the curve; B, median line—50 per cent of the points lie above the curve and 50 per cent below it; C, arbitrary low limit—20 per cent of the points lie below curve

of the size of material available. Hence comparison of the values obtained should be limited strictly to the comparisons drawn in this bulletin.

Under static loads, such as those to which beams in buildings are most often subjected, the work absorbed in bending is not an important property, but rather the stiffness (modulus of elasticity) and ultimate strength (modulus of rupture). On the other hand, when a wood beam is subjected to sudden bending in such a way that the energy of the load can be absorbed, the amount of work involved in bending becomes an important factor in preventing serious failures. Under impact a piece of tough wood that has no greater maximum strength in static bending than a brash piece may successfully resist a shock that would break the brash piece. For example, among the Sitka spruce specimens for which average values are given in Table 1 were one tough and one brash specimen, each having a modulus of rupture of 9,320 pounds per square inch; yet the work absorbed in bending to maximum load was 10.4 inch-pounds per cubic inch for the tough specimen and only 6.6 for the brash one. Consequently, brash wood is especially objectionable under impact.

Table 2 shows the difference in resistance to impact or shock of selected brash and tough ash specimens, as indicated by the maximum drop of a hammer required to break specimens of a specified size under a given method of loading. The fractures of the specimens classified as brash and tough in this table showed brittleness and splintering, respectively. The groups of specimens selected were of approximately the same specific gravity. In specimens selected at random there would be a still greater difference because of the lower average specific gravity and hence lower resistance to shock of brash wood for a species as a whole.

TABLE 2.—*Average shock resistance of brash and of tough, small specimens of commercial white ash tested in impact bending*

Classification	Specimens tested	Specific gravity [1]	Maximum drop of hammer
	Number		*Inches*
Brash	12	0.571	12.7
Tough	10	.574	32.6

[1] Based on volume when air-dry and weight when oven-dry.

Under impact, wood may be bent somewhat beyond its elastic limit without serious injury to the wood or, even if the wood is injured, without serious injury to life or property if it resists complete failure. On the other hand, if its elastic limit is exceeded in a beam subjected to a static load that is maintained, the beam will eventually fail. Under a slowly increasing load, or a static load beyond the elastic limit, the warning that tough wood supplies in progressive splintering gives it a great advantage over a brash piece, which fails without warning. The properties beyond the elastic limit, therefore, often are exceedingly important in the use of wood, and it is in those properties that tough wood excels the most.

One of the chief fundamental characteristics of brash wood is that it has a low ratio of tensile to compressive strength along the grain. Ordinarily the strength of wood in tension is from two to four times that of its strength in compression; in brash wood the ratio is considerably less. Since brash wood usually is relatively low in tensile strength, it breaks on the tension side before much deflection takes place, and hence little work can be absorbed before failure occurs.

ACCIDENTAL FACTORS AFFECTING TYPE OF FAILURE AND TOUGHNESS OF WOOD

Although the type of failure in a piece of wood is an indication of the quality of the wood, there are various accidental factors affecting the character of the failure that are not related to quality. For example, a short beam in fracturing will produce shorter slivers than a long one of the same depth. (Fig. 7.) Fractures in short beams are sometimes so abrupt as to appear brash on superficial examination; the bristlelike slivers in such a fracture are extremely short.

FIGURE 7.—Short, medium, and long white-ash beams showing the effect of varying the length of span on type of fracture in bending

Moderate cross grain may cause long splinters to form, thereby giving the wood an especially tough appearance, even though the actual amount of work involved in the failure may not have been exceptionally large. In fact, slight cross grain in a beam is common, and frequently a fracture of the splintering type starts in such grain. Occasionally in tough wood that is very straight grained no long splinters form, the fracture extending more or less directly across the grain. Although the fracture in such wood may give it a superficial appearance of brashness, the piece may actually have had high toughness. Such a fracture can be distinguished from a true brash one in that portions of the fibers protrude from the break, forming minute bristlelike splinters visible to the unaided eye.

Whether a small stick of wood is loaded on the tangential (flat-grained) or the radial (edge-grained) surface also makes some difference in its capacity to resist shock and in its type of failure, at least in certain species. Specimens of species that separate easily between or within the growth rings are likely, if loaded on the tangential face, to fail in shear along the grain before they fail in tension. This is true especially of specimens short for their depth.

Small specimens of white ash loaded on the radial face showed an average toughness 90 per cent of the average value for matched specimens loaded tangentially; the average specific gravities of the

two groups were the same, 0.601. The corresponding values for Sitka spruce specimens, also well matched, were 58 per cent toughness and 0.418 specific gravity. Similar differences in the toughness of specimens having the load applied on the tangential and the radial faces have been noted in Douglas fir, whereas in black walnut and yellow birch no such consistent difference in toughness was found.

In tangentially loaded specimens of Sitka spruce and Douglas fir, as a rule more splinters were formed than in radially loaded specimens, which broke off more abruptly. The abrupt breakage tended to give an appearance of brashness, although actually most of the wood was of good quality. (Fig. 8.) In ash no such difference in type of failure was found between radially and tangentially loaded specimens.

The specimens used in these tests were very small, five-eighths by five-eighths inch in cross section. Previous tests on specimens of larger size had showed no such difference. Probably the difference does not obtain in structural sizes.

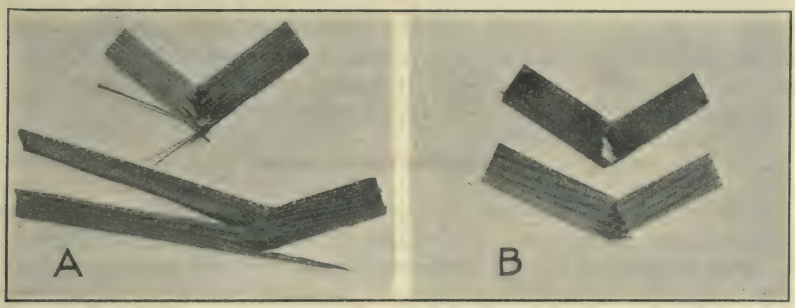


FIGURE 8.—Typical fractures in coast-type Douglas fir tested in a toughness machine: A, Loaded on tangential surface; B, loaded on radial surface

Another accidental factor that may affect the toughness and other bending properties of very small beams containing only a few growth rings is the location of a relatively thick layer of spring wood or summer wood on either the tension or the compression side. Spring wood is relatively weak and when it occurs in either the upper or the lower portions of a small beam, which are the most highly stressed parts, it may cause serious weakening.

In any given kind of wood that is below the fiber-saturation point, deflection under load increases with the moisture content of the wood. The ultimate strength of the fiber decreases, however, so that toughness, which is dependent on load and deflection, is not greatly affected either way by moisture in the wood. Moisture, which is not a part of wood and should therefore be regarded as an accidental factor, affects considerably the type of failure and also certain strength properties of wood; resistance to shock is a property that it does not affect appreciably. Dry wood usually breaks more suddenly and to a greater degree than moist wood, a fact that gives it some of the characteristics of brash wood, but the type of failure normally is splintering. Even when wood that has been dried is resoaked it has more brittleness in fracture than similar wood broken when green.

CAUSES OF BRASHNESS INVESTIGATED

A large number of specimens of brash wood have been examined at the Forest Products Laboratory and compared with tough specimens of the same species, in order to determine the factors responsible for their brashness. In all instances the specimens had been tested in accordance with one of the standard methods for ascertaining the mechanical properties of wood, including a determination of their specific gravity and moisture content (*2*, *16*, *17*, *18*). The specimens were examined for differences in cellular structure and for injury to the cell walls caused by fungi or mechanical agencies. Specimens were also heated at different temperatures and for different periods of time to determine the effect of heat on the strength and the manner of failure of wood. Although many tests were completed, only the results necessary to make clear certain deductions are presented in this bulletin.

SPECIES DIFFERENCES

Although the various species of wood differ greatly in their capacity to absorb work and the extent to which they splinter when bent to the breaking point, no species can be called brash throughout. In even such light species as aspen, redwood, and western red cedar considerable splintering frequently occurs.

ENVIRONMENTAL FACTORS

Different trees of any one species may grow under very different environmental conditions. Even the same tree during its period of life may be subjected to a wide range of growth conditions, especially with respect to the amount of light and moisture that neighboring trees permit it to receive. Changes in the soil as a result of repeated ground fires, flooding, change in drainage, or change in the composition of the forest also affect the growth of trees. The permanent or even temporary bending of trees by the wind may also affect their growth. All these variations in environment affect the kinds and the sizes of cells produced, which in turn determine principally the strength and the other properties of wood, although thus far relatively little is known as to just what effect specific environmental factors have on the quality of the wood (*1*, *14*, *20*, *21*, *22*, *29*). Many of the causes of brashness of wood are related in one way or another to environmental factors affecting tree growth, as is brought out in succeeding pages.

WIDTH OF GROWTH RINGS

The width of the annual layers of growth in itself can have no effect on the strength or the manner of failure of wood, except, as already stated, in thin pieces of species in which the growth rings are composed of well-differentiated portions of spring wood and summer wood. In such pieces wide rings may be responsible for an unusually thick layer of one kind of wood occurring on one or both tangential faces of a specimen. If a load is applied on the tangential face of such a specimen its strength and manner of

failure may be affected greatly by the type of wood in the outer portions, where the stress is greatest. In wood with narrow rings the spring wood and the summer wood alternate more frequently, thus precluding the occurrence of thick layers of either one near a tangential face. In wood of uniform structure, such as that of many native and most tropical species, the width of the annual growth layer is immaterial in this respect. Further, if the load is applied on a radial surface so that the growth rings are parallel to the thrust of the load, it makes no difference whether the tangential sides consist of spring wood or of summer wood, other things being equal.

Rate of diameter growth, however, as indicated by the width of rings, may affect to a great extent the amounts and the quality of different kinds of tissue formed and thereby in turn affect the manner of failure, the strength, and other properties of wood.

In very slowly grown wood of softwoods and of ring-porous hardwoods, such as oak, ash, and chestnut, the spring wood, which is relatively weak and brash in such woods, usually predominates to such an extent that a piece as a whole is brash. Figure 1 shows a typical abrupt fracture, denoting brittleness, in slowly grown hickory wood, in contrast with a splintering fracture, denoting toughness, in wood, having wider rings, from the same tree. The relative width of the rings and the position of the two specimens in the log, from which they were cut, are shown in Figure 2, and photomicrographs of cross sections of the two specimens appear in Figure 3. In the Sitka spruce specimens studied the toughness value was found to drop off as the rings became very narrow.

In diffuse-porous hardwoods, such as yellow poplar, black walnut, and birch, very slowly grown wood usually has a relatively high percentage of porous tissue and a low percentage of fibrous tissue, thereby making the wood as a whole brash. Figure 9 pictures the difference in porousness of narrow-ringed and wide-ringed yellow poplar. In black walnut an increasing number of pores per unit area of the cross section was found to occur as the width of the rings decreased.

On the other hand, rapid growth, causing wide growth rings, does not necessarily mean a high degree of toughness. In conifers of very rapid growth the spring wood usually is relatively wide. This tends to make the wood light and brash. Further, compression wood (p. 22), which also has relatively wide rings, tends to be brash although it is heavy. In hardwoods, on the other hand, wide rings, as a rule, mean heavy, strong wood. Exceptions occur, however; for instance, the wide-ringed wood formed in swelled butts of ash and tupelo gum from very wet swamps is light and brash.

Too much reliance should not be put on ring width in judging the quality of wood, since for any ring width large variations in strength may occur, because different growth conditions may produce similar rates of growth but different proportions of the various types of tissues found in wood (*21*). Table 3 shows that in the ash, the oak, and the Sitka spruce tested in bending large differences occurred in the average work or toughness values of the brash and the tough specimens, without significant difference in the average width of the rings.

PERCENTAGE OF SUMMER WOOD

In judging the mechanical qualities of those species of wood in which the spring wood and the summer wood are well differentiated, a considerably better criterion than width of growth ring is the per-

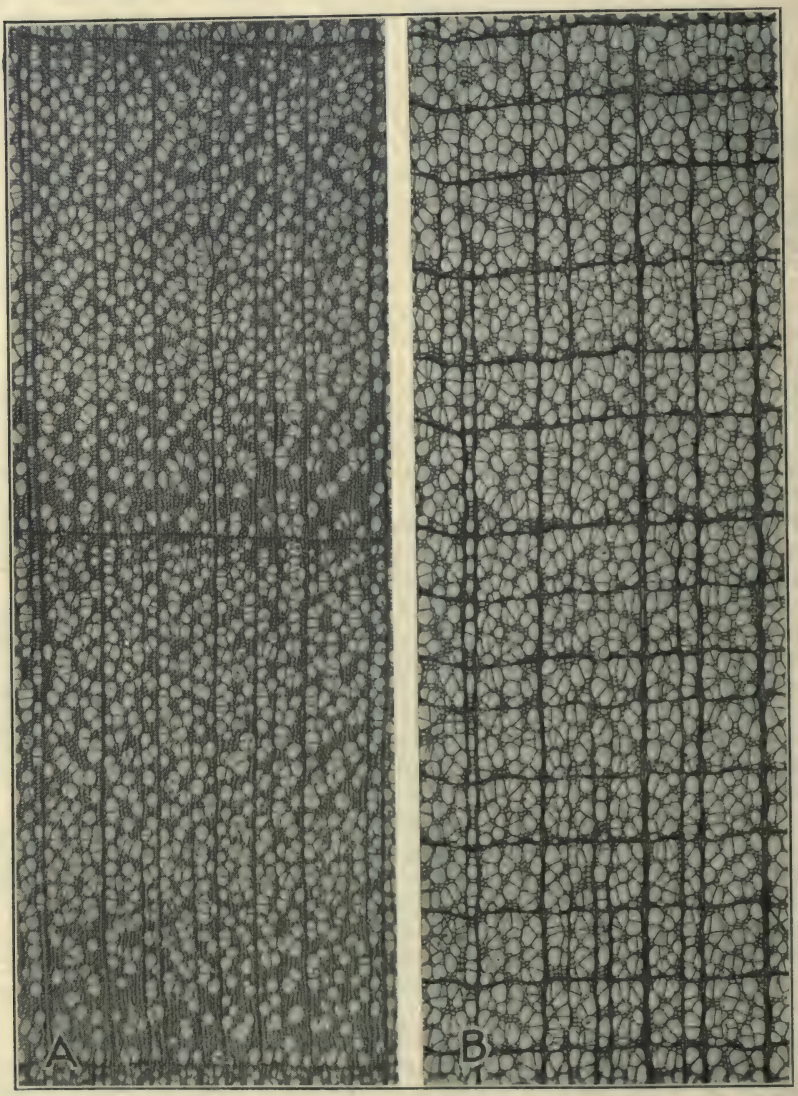


FIGURE 9.—Cross sections of yellow poplar: A, Wide-ringed wood of specific gravity 0.41; B, narrow-ringed wood of specific gravity 0.31, having more pores and fewer wood fibers (the small cells) than the heavier wood. × 20

centage of summer wood. Wood with a small percentage of summer wood and consequently a high percentage of spring wood usually is light in weight, weak, and brash. Figure 10 shows brash spring wood in tough specimens of ash and Douglas fir. Table 3, however, shows that the percentage of summer wood is not always the deter-

mining factor in brashness; brash and tough specimens may have virtually the same percentage of summer wood and yet have widely different toughness values. This is due to the fact that preexistent compression failures (p. 27), which bear no relation to the amount of summer wood present, were a common cause of brashness in specimens of the species in Table 3; that a deficiency of wood fibers, even though the percentage of summer wood was normal, obtained in many of the oak specimens; and that compression wood (p. 22), which always has a high percentage of summer wood, occurred in some of the brash Sitka spruce specimens.

TABLE 3.—*Average number of growth rings per inch and percentage of summer wood in brash and in tough specimens of various species of wood of approximately the same specific gravity but of widely different shock-resisting capacity*

Species of wood	Nature of test	Classification of specimens	Specimens examined	Average specific gravity [1]	Average work to maximum load	Average maximum drop of hammer	Average toughness value	Rings per inch	Average amount of summer wood
			Number		*In.-lbs. per cu. in.*	*Inches*	*In.-lbs. per specimen* [2]	*Number*	*Per cent*
Commercial white ash.	Static bending.	Brash	15	0.562	7.1			12.7	66.4
		Tough	20	.566	22.1			12.6	59.9
	Impact bending.	Brash	12	.571		12.7		10.7	66.0
		Tough	10	.574		32.0		11.4	60.4
Commercial white oak.	Toughness	Brash	51	.656			124.1	15.6	52.3
		Tough	49	.655			339.9	14.7	54.2
Sitka spruce	Toughness	A selected number of the 20 per cent lowest in toughness for specific gravity.	176	.389			48.3	10.1	
		do	167	.387			47.8		12.9
		A selected number of the 20 per cent highest in toughness for specific gravity.	178	.373			134.8	13.3	
		do	176	.373			133.6		14.0
	Static bending.	Brash	17	.390	6.4			16.4	
		Tough	14	.391	10.3			15.5	

[1] Based on volume when air-dry and weight when oven-dry.
[2] Size of specimen: White oak, ¾ by ¾ by 12 inches; Sitka spruce, ⅝ by ⅝ by 10 inches.

In some hardwoods, as swamp ash, the summer wood may be wide but not dense. (Fig. 11.)

SAPWOOD AS COMPARED WITH HEARTWOOD

No generalization on the relative toughness of sapwood and of heartwood or on the occurrence of brash wood in either can be made. In old, slowly growing trees the sapwood is frequently low in toughness and may even be brash, on account of the large percentage of spring wood or other porous tissue that it contains. The brash specimen in Figure 1 is the more recently formed sapwood of an old, mature hickory tree, whereas the splintered specimen, which was taken from the same tree, is heartwood formed when the tree was young.

In young, vigorously growing trees, the sapwood often ranks higher in toughness than the heartwood. This is also true in softwoods because the sapwood does not include the wide rings often occurring at the center, which usually have a high percentage of spring wood and are brash. It also holds for trees in general because the heartwood of young trees contains more knots and other irregularities in the grain than the sapwood does.

The effect of differences in infiltrated materials in sapwood and heartwood is discussed under the head of Chemical Composition, page 35.

CELLULAR STRUCTURE OF WOOD LOW IN DENSITY FOR ITS SPECIES

By density of wood is meant essentially the amount of cell wall present in comparison with the space in the cell cavities; specific gravity is often used as a measure of density. Considerable varia-

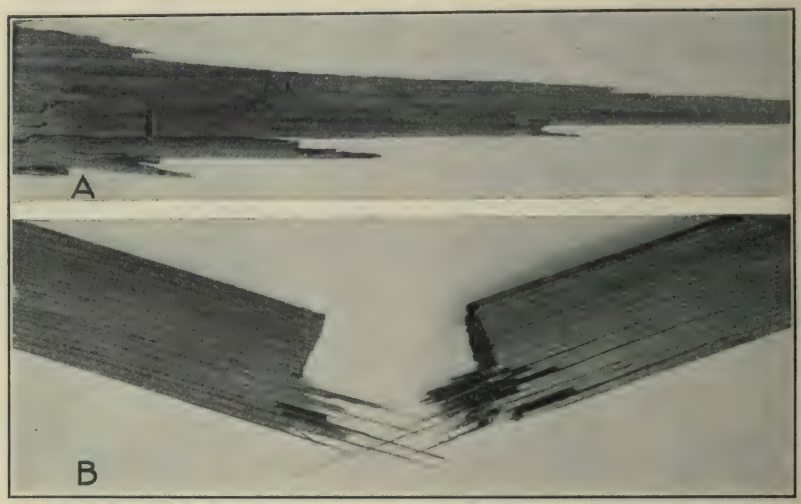


FIGURE 10.—Abrupt breaks through successive layers of spring wood, giving the spring wood an appearance of brashness, and long fractures through layers of summer wood, on which toughness largely depends: A, Splinter of white ash; B, test specimen of Douglas fir, reference is made to lower half, or tension failure in specimen

tion in density occurs within each species of wood because of differences in the growth conditions of individual trees. Obviously the smaller the amount of wood substance in a given volume of wood the weaker it will be, other things being equal (*8*). General relations between the strength properties and the specific gravity of the different species of wood have been worked out at the Forest Products Laboratory (*19*). Within a species the same general relationships also hold but, as a rule, in addition to weakness, wood of density that is low for a species also shows brittleness in fracture. (Figs. 5 and 6.) In comparing different species, however, brashness does not always accompany low density; that is, the wood of species light in weight, such as red cedar, basswood, and cottonwood, is not considered characteristically brash, although these species may not sliver so much as some of the heavier and tougher

woods. The characteristic brashness of wood low in weight for a species is due to the preponderance of certain types of fibers and other cells, which are relatively scarce or even entirely absent in normal wood of the same species.

In order to discuss more fully the structure of wood of low density and the relation of such wood to brashness, it will be necessary to consider the softwoods and the hardwoods separately.

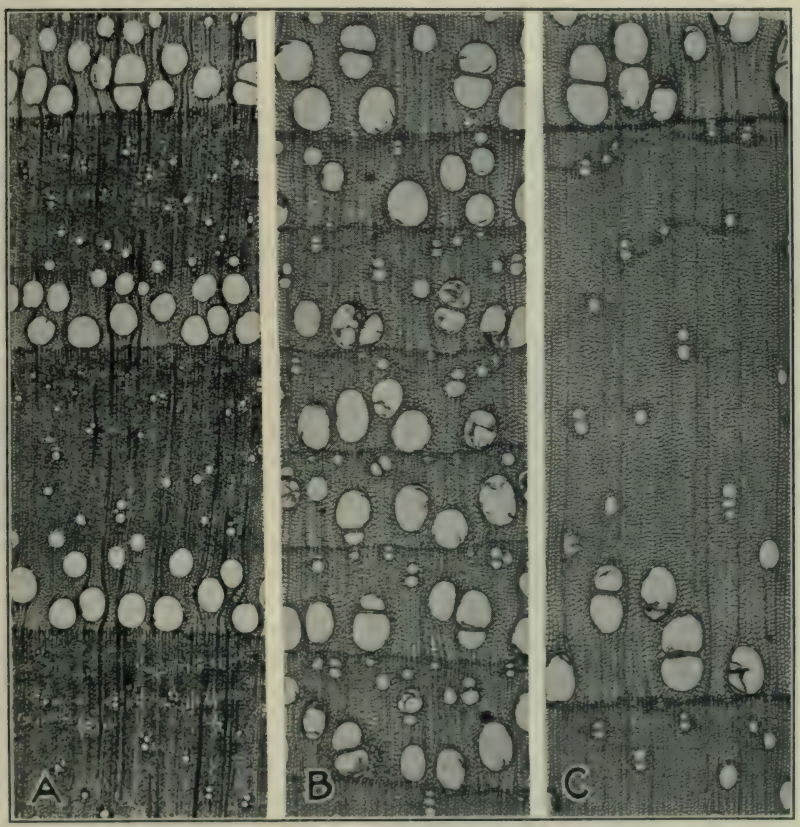


FIGURE 11.—Cross sections of white ash: A, Wood of average density and ring width; B, wood low in density because of narrow growth rings and a small percentage of summer wood; C, wood low in density because of large cavities and thin walls in the fibers, even though the growth rings are wide—a type of wood found in swelled butts of trees growing in inundated swamps. × 20

SOFTWOODS

In the softwoods, or conifers, two types of fibers, called tracheids, are normally present. They are those having large cavities and thin walls, formed in the inner part of each growth ring and making up the spring wood, and those having thick walls and small cavities, formed in the outer part of each growth ring and making up the summer wood. Obviously the larger the percentage of summer wood in a piece of wood, the heavier and stronger it will be, other things being equal.

In addition to the differences just mentioned, spring wood differs from summer wood in the structure of the fiber walls. All wood fibers and also, as far as is known, other cells in wood are made up of fibrils, which wind around the cell cavity.[4] The slope of the windings varies greatly, from an angle of 3° to 15° with the cell axis in normal summer wood of softwoods to 15° to 35° in normal spring wood. These figures apply to the major portion of the cell wall. Ritter (*24*) found an extremely thin layer of fibrils extending around the outside of some fibers at an angle of nearly 90° with the longitudinal axis of the fiber.

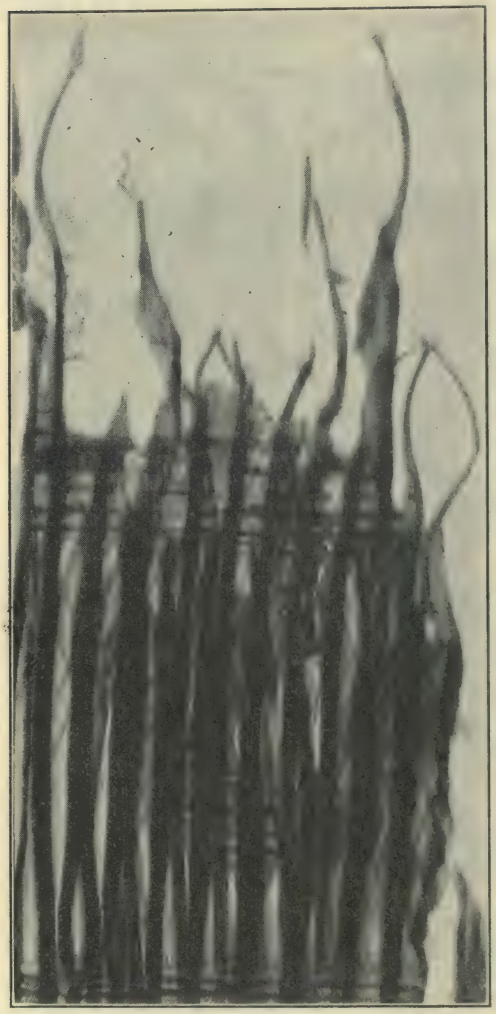


FIGURE 12.—Thin longitudinal section at a tension failure in Sitka spruce, showing the spiral fracture of individual fibers. × 125

The difference in the slope of the fibrils in the spring wood and in the summer wood is also responsible for differences in the strength and the manner of failure of these two types of wood. Although these fibrils are too small to be seen individually even with a high-power microscope, investigation by other means has shown that when a piece of wood fails in tension the individual fiber walls frequently are torn apart obliquely (*5*, *26*) (figs. 12 and 13), the direction of the failure in each fiber corresponding largely to the orientation of the fibrils. This indicates that there is a line of weakness between adjacent fibrils; the indication is substantiated by X-ray diffraction investigation (*6*).

Obviously the fibrils must also break somewhere, as well as separate from each other, in order for a fracture to be complete, but the greater the slope of the fibrils the smaller will be the failure

[4] These fibrils should not be confused with the spiral thickening found on the inner surface of the wall in some cells of certain species.

within them and the greater the failure between them. If the fibrils should make an angle of nearly 90° with the cell axis, a condition approached in some hardwood vessels, then failure in tension along the grain would be almost entirely between fibrils and the resistance offered by the cell wall would be relatively small.

In a large number of coniferous woods examined, the twist was always found to be in a right-hand direction. Therefore, in contiguous walls of two adjoining fibers the slope of the fibrils, when viewed from the same side, would be in opposite directions in the two walls. This fact, however, seemingly does not vitiate the statement that the strength decreases with the slope of the fibrils, other things being equal.

FIGURE 13.—Thin longitudinal section at a tension failure in spongy white ash, showing the spiral fracture of individual fibers and the corresponding slope of the slitlike pits in the fiber walls. The photograph was taken by polarized light. × 350

Another reason why thin cell walls are weaker is that they contain relatively less of the secondary cell wall which, because of its fibrillar structure of moderately oblique slope, presumably is stronger than the rest of the cell wall.

Spring wood of softwoods, therefore, is weaker than summer wood for three reasons: (1) The relatively small amount of wood substance present, as evidenced by the thin cell walls and the large cell cavities, (2) the relatively large slope of the fibrils in the secondary wall, and (3) the presence of a relatively greater proportion of the middle lamella and the immediately adjoining layer with their presumably lower tensile strength. On account of the relatively great slope of the fibrils spring wood always breaks off abruptly (fig. 10), whereas splinters, if produced, occur in the summer wood. With very little summer wood present the whole piece may be brash. These structural features, therefore, probably explain the brashness of softwoods light in weight for their species.

Incidentally, spring-wood fibers contain more pits than summer-wood fibers, but the available evidence is that the number of pits has little if any effect upon the strength of a fiber. In fact, it is not at all certain that a normal spring wood pit is weakening, since the fibrils immediately surrounding the pit orifice run concentrically around the opening, thereby binding the cell wall more firmly than in the unperforated portion (*9*).

HARDWOODS

Woods belonging to the hardwood group have a more complicated structure than those of the softwood group. In addition to the fibers in hardwoods, there are present in considerable numbers specialized vessels, also called pores, for conducting sap, and vertical parenchyma cells for storing food, which are respectively absent and scarce in softwoods. Each species of hardwood shows considerable variation in the amount of fiber, of vessel, and of parenchyma tissue, the relative amounts of each depending on the growth conditions under which the wood was formed.

Hardwoods may be light in weight for two reasons: (1) The preponderance of nonfibrous tissue (vessels, tracheids, and parenchyma) over wood fibers, and (2) the presence of wood fibers with thin walls and large cavities in place of the more normal ones with thicker walls and smaller cavities. The first condition occurs usually as a result of slow growth (figs. 3, B; 9, B; and 11, B) and the second is found in the swelled butts of hardwoods growing in very wet swamps. (Fig. 11, C.)

The vessels usually have a very oblique orientation of the fibrils, which often approaches an angle of 90° with the longitudinal axis. In ring-porous woods, vessels are abundant in the spring wood, which accounts for its characteristic brashness, no matter how tough the wood as a whole may be. (Fig. 10, A.) If little summer wood is present, as usually is the case in very slowly grown wood of such species, the whole piece is light, weak, and brash. The toughness of ring-porous wood, therefore, depends largely on the summer wood, as does toughness in conifers. In diffuse-porous hardwoods, in which the vessels are scattered more or less evenly among the wood fibers, an overabundance of vessels (fig. 9, B), a condition that comes from adverse growth conditions, also makes for brashness.

In the wood from swelled butts of ash, tupelo gum, and some other hardwoods growing in very wet swamps of the South, not only are the wood fibers large-lumined and thin-walled, but the fibrils make angles of 20° to 50° with the cell axis, as compared with 3° to 10° in the summer wood of normal tough ash. This orientation of the fibrils causes additional weakness and abrupt failures across the grain in bending for the same reasons given for the spring wood of softwoods. Figure 13 shows the oblique orientation of the pits in spongy ash, and Figure 14 shows the brash type of failure characteristic of such wood.

CELLULAR STRUCTURE OF WOOD OF MEDIUM AND OF HIGH DENSITY FOR ITS SPECIES

Brashness is not confined to wood of low density; it occurs also in wood of medium and of high density, although not so commonly. Further, although brash wood of high density ranks low in shock-resisting capacity for its specific gravity, it still may actually have higher shock resistance than a tough specimen of lower specific gravity and correspondingly lower toughness of the same species. This fact is shown by some of the brash specimens of high specific gravity in Figures 5 and 6. To determine causes of brashness other

than those associated with low specific gravity, selected brash and tough specimens of moderate to high specific gravity of various species were studied.

SCARCITY OF WOOD FIBERS IN OAK

Some test specimens of oak not low in specific gravity were brash because they contained relatively small amounts of wood fiber. In them, weaker cells, mostly parenchyma and vascular tissue, occurred to a greater extent than usual. On account of their structure, wood fibers are considered the principal strength-giving elements of hardwoods. Oak has a peculiar arrangement of tissues in that its wood fibers are bunched, appearing on cross sections as islands interspersed with other tissues. This arrangement of the tissues makes it possible to determine approximately how much of the

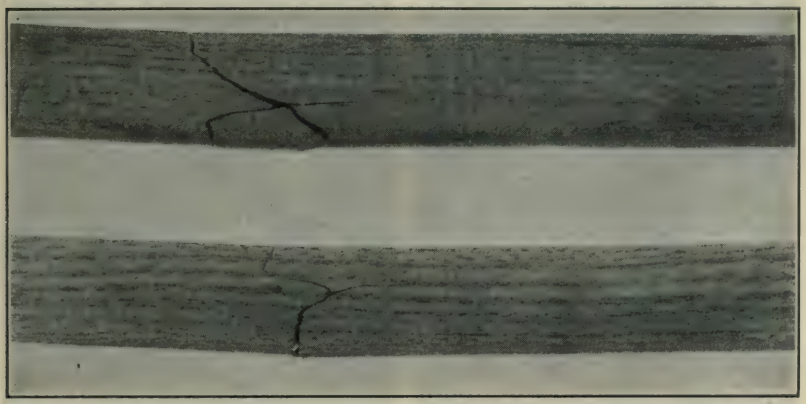


FIGURE 14.—Abrupt fractures in white ash of low density

volume of a piece of oak consists of wood fibers, scattering strands of parenchyma cells included. Figure 15 shows cross sections of two pieces of oak, considerably magnified, in which black lines outline the islands of wood fibers. A much larger proportion of the cross section of the tough piece is occupied by the wood-fiber areas. Measurements over areas larger than that of the illustration gave percentages of 32.4 and 12.6 for wood fiber of the tough and the brash specimens, respectively. Such differences are not necessarily due to differences in rate of growth, since wide-ringed oak may have little wood fiber, although as a rule very slowly grown oak has only a small percentage of wood fiber. They are due to certain differences in growth conditions that affect the formation of wood fiber, although just what conditions make for the production of a large proportion of wood fiber is not known.

Oak with little wood fiber has a dull and lifeless appearance on smoothly cut end surfaces, and on cutting shows a more cheesy consistency than oak with a large percentage of wood fiber. For purposes for which a high degree of strength is not required such oak is often preferable because it works more easily, and in addition possibly shrinks and warps less.

Oak and a number of other hardwoods have two kinds of wood fibers: One, with a thick wall of apparently uniform composition, is normal, while the other, although it has an outer wall similar to that of the first except for its thinness, has also an inner layer that gives a typical cellulose reaction with certain stains and evidently has shrinkage characteristics different from those of the outer wall, to judge by the way this wall often pulls away from the outer one. The second kind of fibers have been called gelatinous and mucilaginous, although these terms are not properly descriptive.

Proceeding on the assumption that the presence of gelatinous fibers might affect the toughness of oak, stained microscopic sections of some 50 brash oak specimens and 50 tough specimens of

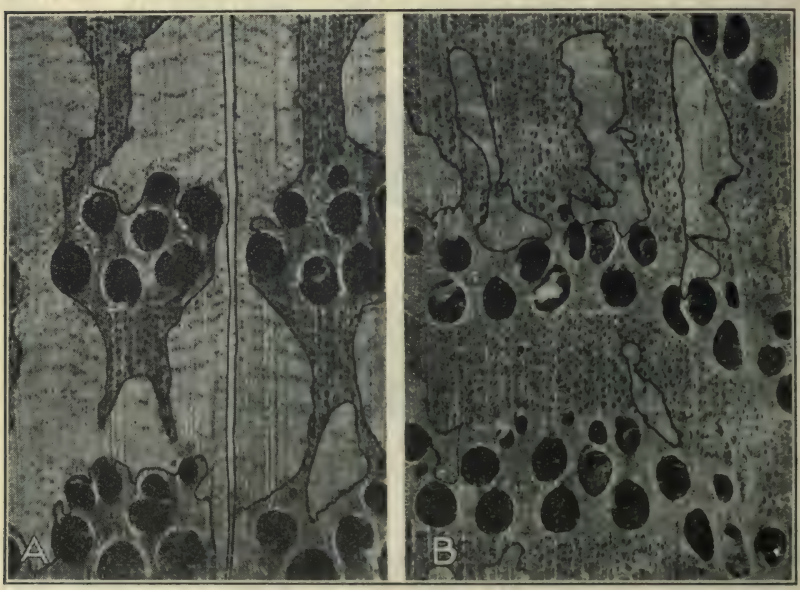


FIGURE 15.—Thin cross sections, in negative, of white oak specimens having the same specific gravity (0.66) and nearly the same width of growth ring but with widely different percentage volumes of wood fibers. The wood fibers occupy the light-colored areas, which are outlined in black. The toughness of the brash wood was 63 per cent that of the other. A, Tough specimen; B, brash specimen. About × 20

about the same range in specific gravity were examined to see whether gelatinous fibers predominated in either group. No relation between the percentage of gelatinous fibers and toughness was found; the gelatinous fibers occurred sporadically in both groups.

VOLUME OCCUPIED BY WOOD RAYS

Since the ray cells in wood are oriented mostly with their long axes radial with respect to the growth rings, they presumably do not contribute so much to the strength of a piece stressed along the grain, especially in tension, as most of the cells that lie with their long axes parallel to the grain, for the same reason that wood in general is not so strong in compression and in tension at right angles to its fibers as parallel to them. An investigation was therefore

made of the relative volumes occupied by the rays in brash and in tough wood of several species to determine whether the volume occupied by the rays might appear to be related to brashness.

For this purpose, as for most of these studies, brash and tough specimens of the same specific gravity were selected for each species of wood investigated so as to eliminate as far as possible all differences except the one under investigation.

Table 4 gives the average relative amounts of ray tissue in brash ash, oak, and Sitka spruce, respectively, as compared with those in tough wood of the same species and same specific gravity.

TABLE 4.—*Relative amounts of ray tissue in brash and in tough specimens of ash, oak, and spruce, respectively, of the same average specific gravity*

Species of wood	Nature of test	Classification of specimens	Specimens examined	Average specific gravity [1]	Average work to maximum load	Average maximum drop of hammer	Average toughness value
			Number		*In.-lbs. per cu. in.*	*Inches*	*In.-lbs. per specimen* [3]
Commercial white ash	Static bending	Brash	15	0.562	7.1		
		Tough	20	.566	22.1		
	Impact bending	Brash	12	.571		12.7	
		Tough	10	.574		32.6	
Commercial white oak	Toughness	Brash	46	.660			124.9
		Tough	43	.660			348.3
Sitka spruce from Washington	do	Brash	36	.380			91.1
		Tough	36	.380			214.3
Sitka spruce from Alaska	do	Brash	36	.410			95.5
		Tough	36	.411			214.7

Species of wood	Ray cells in a circular tangential area 0.7 mm in diameter	Ray cells in all small rays per circular tangential area 0.7 mm in diameter	Average volume occupied by large rays in terms of total volume	Rays per rectangular tangential field 0.8 by 4 mm having specified number of cells in height [2]				
				1–5	6–10	11–15	16–20	More than 20
	Number	*Number*	*Per cent*	*Number*	*Number*	*Number*	*Number*	*Number*
Commercial white ash	213.5							
	202.9							
	216.2							
	220.2							
Commercial white oak		191	8.18					
		175	5.68					
Sitka spruce from Washington				34.2	42.7	11.4	1.9	0.3
				35.7	43.7	12.7	1.6	.4
Sitka spruce from Alaska				39.0	38.3	13.2	3.2	.9
				37.5	40.7	13.5	3.1	1.0

[1] Based on volume when air-dry and weight when oven-dry.

[2] The rectangle was oriented with the narrow side running transversely across the rays and fibers so that a minimum number of rays were cut. The cut rays were counted as entire rays of whatever number of cells were visible.

[3] Size of specimen: ¾ by ¾ by 12 inches.

The relative volumes occupied by all the rays in white ash and by the small rays in oak were determined by counting the number of ray cells in several circular areas on tangential sections of the wood cut from the tension side of the specimen near its point of failure. Counts for such areas were averaged for each specimen. In the oak the volume of the large rays was determined by finding the total

width of such rays along a number of transverse lines on a tangential surface and then expressing the result in terms of the total length of the lines. In Sitka spruce, instead of counting the number of ray cells per unit area, the rays were counted by height classes, in terms of number of cells, which with large numbers gives virtually the same results. Fusiform rays containing resin ducts were omitted from the table since they averaged only one to one and a half per unit field.

The ash had no appreciable difference in the number of ray cells in the brash and in the tough material, which shows that these structural elements were not responsible to any considerable extent for the large differences in shock resistance.

In the oak many of the brash specimens had an appreciably larger volume of large rays and a slightly greater number of small ray cells than the tough specimens. It is impossible, however, to say how much the greater volume of large rays contributed to brashness since, in general, a decrease in volume of wood fiber accompanied an increasing volume of ray tissue. This relationship also explains why the specific gravity of the brash and the tough oak specimens was the same, although the pieces differed greatly in the amount of wood fiber present; the ray tissue is almost as dense as the wood-fiber tissue, and in addition the ray cells as well as the vertical parenchyma cells that partly replaced the wood fibers in many of the brash specimens, unlike the wood fibers, contained considerable amounts of deposits, which add to the weight but not to the strength.

In the Sitka spruce, in general, there was no appreciable difference in the amount of ray tissue present in the brash and the tough specimens. Hence that factor can be disregarded as a possible cause of brashness except possibly in abnormal growth, such as that which occurs as a result of injury or very unfavorable growth conditions. No such abnormal material, however, was observed in this study.

COMPRESSION WOOD

One of the outstanding causes of brashness in coniferous woods is compression wood, which is a relatively wide-ringed type of wood formed on the lower, or compression, side of leaning coniferous tree trunks and of branches. (Fig. 16.) Compression wood is further characterized by a high proportion of summer wood, less dense than normal, in each growth ring; rounded instead of flattened summer-wood tracheids; numerous intercellular spaces among the summer-wood tracheids (fig. 17); and spiral striations and spiral cracks running at a rather oblique angle in the walls of the summer-wood tracheids. Because of the high percentage of summer wood that it contains, even though this summer wood is not so dense as normal summer wood, compression wood frequently ranks relatively high in specific gravity, especially in species that normally do not have heavy wood. All stages of compression wood from that barely distinguishable from normal wood to that showing a pronounced difference may be found in all softwood species. It does not occur in hardwoods.

Compression wood, when broken in bending, invariably displays brittleness, although the break usually does not extend straight

across the piece but either zigzags back and forth, producing blunt splinters, or more often extends directly across the grain from the tension side inward a short distance and then branches out in two directions diagonally across the piece, like a wide Y. (Figs. 18 and 19.)

In the green condition compression wood compares favorably with normal wood in most of its mechanical properties, on a unit-size basis, and frequently excels; the one outstanding exception is stiffness, in which compression wood is relatively low. On a unit-

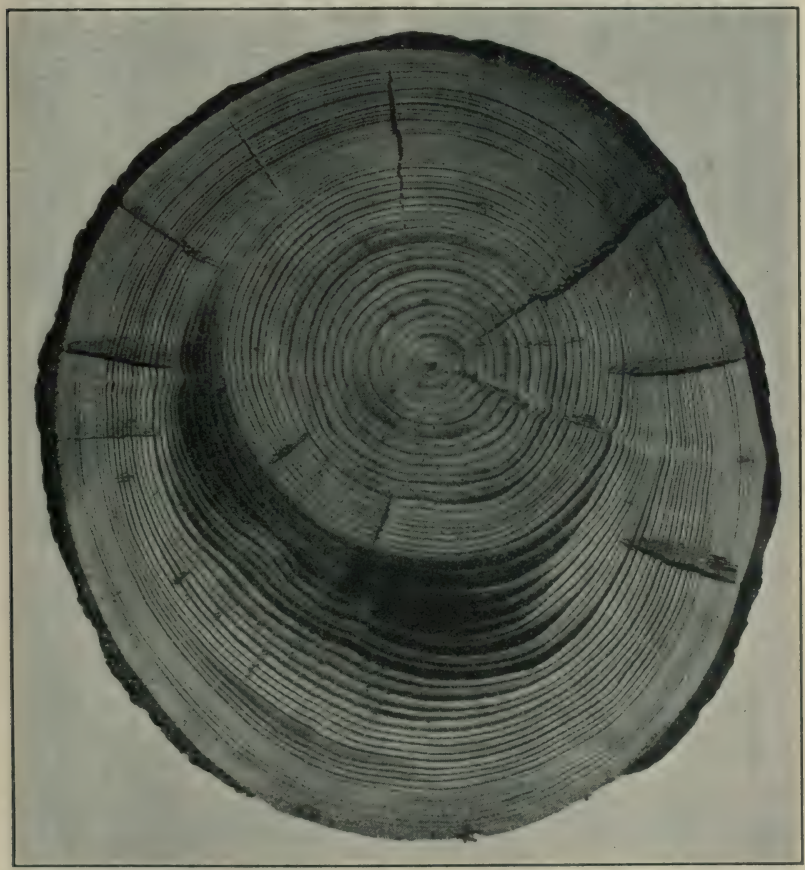


FIGURE 16.—Compression wood, appearing as dark, wide portions of growth rings, in a cross section of an eastern spruce log

weight basis normal wood is usually superior. Upon drying, however, compression wood does not increase in strength so much as normal wood, and consequently dry compression wood, on a unit-size basis, is frequently weaker than normal wood. On a unit-weight basis, dry compression wood is often greatly inferior in strength. For most uses the properties of dry wood are more important than those of wet wood, and consequently the following data refer only to dry wood. The property of toughness, or shock resistance, which is the property most concerned in brashness, is

a highly variable one, and although some compression wood is the equal of normal wood in this respect other compression wood is inferior. Because of its erratic nature and because it usually fails

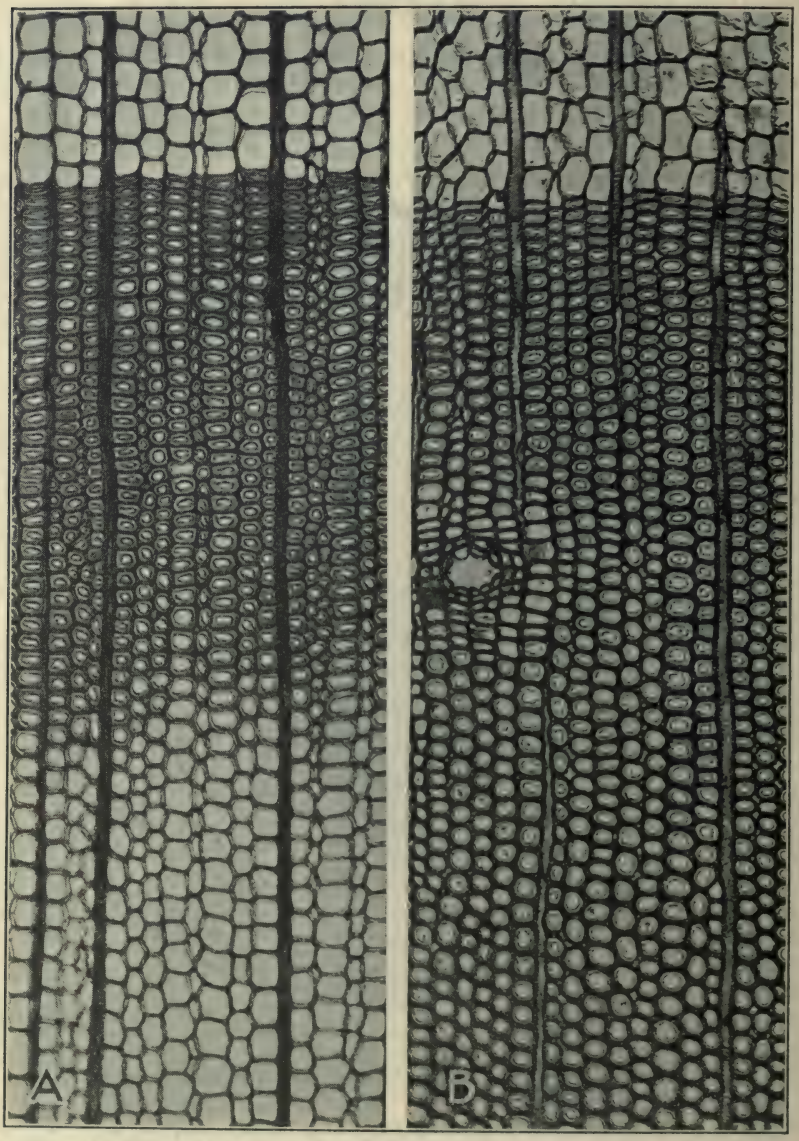


FIGURE 17.—Thin cross sections showing rounded summer-wood fibers and intercellular spaces in compression wood but not in normal wood of Douglas fir: A, Normal wood; B, compression wood. × 100

suddenly and completely when it does fail in bending, compression wood should not be used for any purpose for which tough wood is required. Figure 6 shows that Sitka spruce specimens containing compression wood usually gave low values in the toughness test,

although many of them were above the average in specific gravity. This graph represents some 450 specimens, cut from seven trees, very few of which contained pronounced compression wood. After

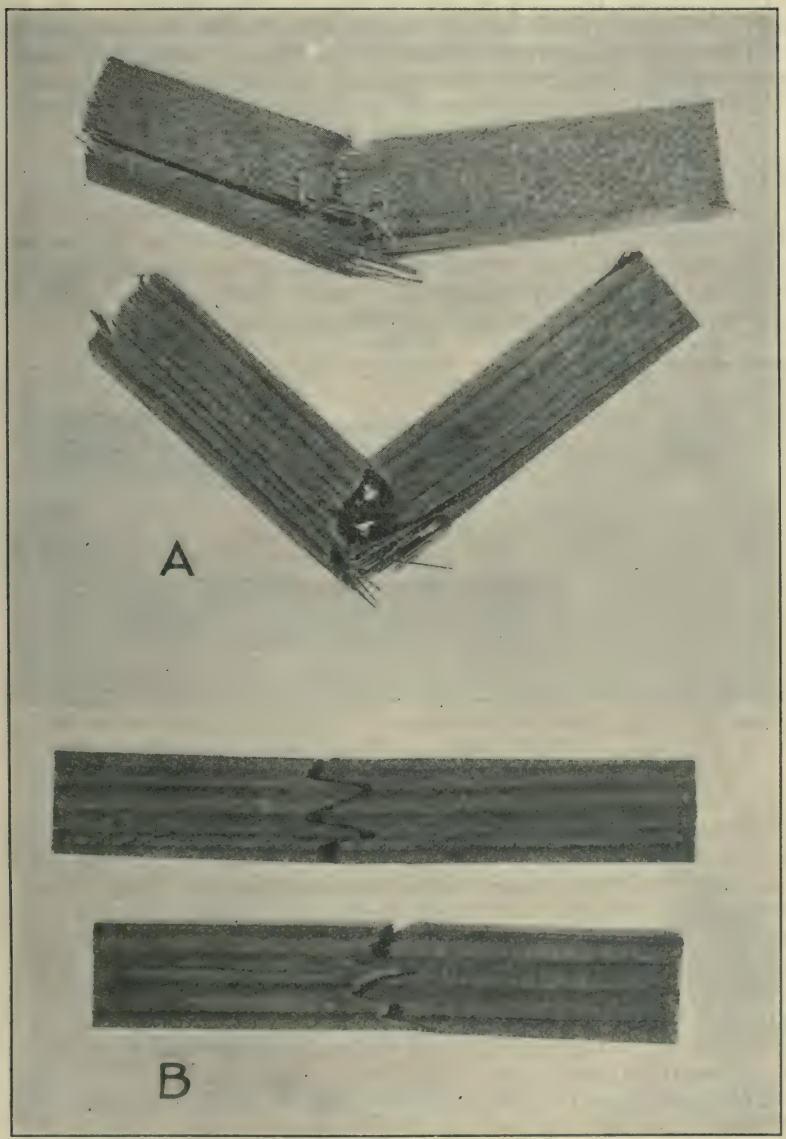


FIGURE 18.—Typical fractures in Sitka spruce loaded on a tangential surface: A, Normal wood; B, compression wood

the specimens represented in Figure 6, as well as about 450 matched specimens tested on the radial face, had been divided into three groups, namely, the 20 per cent lowest in toughness for their specific gravity, the 20 per cent highest in toughness for their specific grav-

ity, and the intermediates, the percentage of specimens containing compression wood in each group was found to be as follows: In the lowest 20 per cent, 17.6 per cent of the group; in the intermediate 60 per cent, 2.3 per cent of the group; in the highest 20 per cent, none. Although these figures do not necessarily indicate the relative prevalence of compression wood in Sitka spruce, they do indicate the effect of compression wood in reducing the toughness values.

Undoubtedly the great slope of the fibrils in the walls of the fibers in compression wood, which is indicated by the spiral striations already referred to, causes some weakening, but this is compensated for in part by the comparatively high specific gravity of that wood. One of the chief mechanical characteristics of compression wood is that it is not stiff; it bends before it breaks more than normal wood bends, probably because of the great slope of the fibrils; the resulting spring-like structure presumably allows the fibers to stretch more easily and to a greater extent before they break.

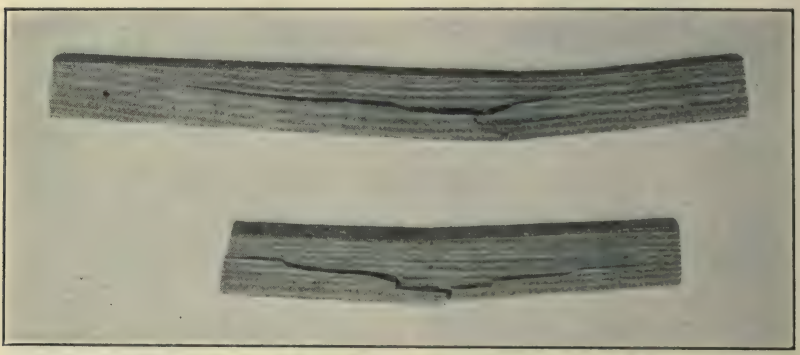


FIGURE 19.—Typical simple-tension failures in compression wood of Douglas fir, also characteristic of other brash wood

FIBER LENGTH

A common but fallacious opinion about wood is that its bending strength depends largely upon the length of its fiber. Although the tensile strength of cordage and fabric depends to a large extent on the length of the fibers from which they are made, it is not true of wood. When a piece of wood fails in bending, it fails first in compression along the grain, which does not involve slippage between the fibers. When tension failure occurs in bending, the fibers do not again slip by one another, as in a cord; transverse fracture of the individual fibers occurs, showing that the strength of the fiber and not its length is the determining factor. This is due to the fact that the fibers are grown together tightly; the bond uniting them would have to shear over comparatively large areas if slippage should occur.

In this study the fiber length was determined for only one group of brash and another of tough Sitka spruce specimens; both groups had about the same average specific gravity. No significant differences in average length were found, although the brash specimens did have a slightly shorter average, possibly because the fibers in compression wood, which occurred in some of the brash speci-

mens, are shorter than those in normal wood. Forsaith (*8*), who found even greater differences in fiber length of brash and of tough specimens of various species in working with exceptionally light brash and heavy tough wood within a species, also came to the conclusion that fiber length has no direct relation to strength. Gerry (*10*) reached a similar conclusion with respect to Douglas fir after comparing fiber length and strength data of the same specimens.

THICKNESS OF FIBER WALLS AND DIAMETER OF FIBER CAVITIES

Since the material forming the walls of wood cells is fairly uniform in density, it follows, in general, that wood light in weight has either thinner cell walls or larger cell cavities, or both, than heavier wood. That such is the case is readily apparent on examining thin cross sections of light wood and heavy wood under the microscope. The specific gravity of wood, therefore, is usually a sufficient indication within a species of the amount of cell wall present and to a large extent of the strength, and it is much easier to make such a determination than to take measurements under the microscope.

There is a possibility, however, that of two pieces of wood having the same specific gravity, one may contain less wood substance than the other, the deficiency in wood substance being made up by other materials deposited in the cell cavity or even in the cell wall. It is reasonable to assume that materials deposited in the cell cavities do not add to the strength of wood, although they add to the weight, unless the deposits are so abundant as to fill entirely a large percentage of the cell cavities. In that event they may affect certain strength properties by the mechanical support they give to the cell walls. In the oak with a low percentage of wood fiber but a high percentage of ray tissue, already referred to, the abundant material in the parenchyma-cell cavities probably added to the weight but not to the strength.

Averages of the measurements of thickness of cell walls and diameter of fiber cavities, made in the study of brashness, are given in Table 5 for black walnut, oak, and Sitka spruce. Although the number of measurements were limited, these averages show no appreciable differences between the brash and the tough specimens. The parenchyma cells and the tracheids that may develop in oak in place of wood fibers have thinner walls and larger cavities than wood fibers usually have, and for that reason, as well as because the walls of such cells are built up differently, oak, having a small percentage of wood fiber, is deficient in strength, irrespective of its specific gravity.

In wood of different specific gravities, within a species, there may be large differences in the thickness of the cell walls or in the size of the cell cavities, with corresponding differences in strength; Forsaith (*8*) found this in southern cypress, yellow poplar, and white ash.

EXISTING COMPRESSION FAILURES

A compression failure is a permanent deformation of cell walls produced in compressing wood along the grain beyond its elastic

limit. The compression may occur as a result of direct end loading, as in a post, or as a result of transverse loading, as in a beam. The deformation may be a distinct buckling of the fibers, pronounced enough to be readily visible to the unaided eye (fig. 20, B), it may be only faintly visible, or it may be merely a slight localized crinkling in the cell wall, visible only with a microscope, preferably a polarizing one, in thin sections of the wood, in which it appears as fine crosshatchings of the fiber wall without any noticeable displacement of the fiber as a whole. (Fig. 21.) Compression failures themselves are discussed in detail elsewhere (*3*, *26*).

TABLE 5.—*Average thickness of fiber wall and average diameter of fiber cavity in brash and in tough specimens of the same specific gravities, of various species of wood tested in the toughness machine*

Species of wood	Classification of specimens	Specimens examined	Average specific gravity [1]	Average toughness value	Average thickness of fiber wall				Average diameter of fiber cavity
					Spring wood		Summer wood		
					Radial	Tangential	Radial	Tangential	
		Number		*In.-lbs. per specimen* [2]	*Millimeter*				*Millimeter*
Black walnut	Brash	49	0.583	229.6	[3] 0.0035				[3] 0.0097
	Tough	49	.585	465.3	[3] .0035				[3] .0090
Commercial white oak.	Brash	51	.656	124.1	[4] .0048				[4] .0041
	Tough	49	.655	339.9	[4] .0050				[4] .0043
Sitka spruce from Washington.	Brash	20	.379	87.0	0.0024	0.0024	0.0045	0.0068	.....
	Tough	20	.379	203.5	.0024	.0023	.0048	.0070	.....
Sitka spruce from Alaska.	Brash	20	.417	95.9	.0026	.0026	.0046	.0065	.....
	Tough	20	.417	216.9	.0027	.0027	.0044	.0064	.....

[1] Based on volume when air-dry and weight when oven-dry.
[2] Size of specimen: Black walnut, ¾ by ¾ by 16 inches; other species, ¾ by ¾ by 12 inches.
[3] The fibers measured were selected at random throughout the growth ring.
[4] These values represent only nongelatinous fibers in summer wood, which were selected at random.

Wood containing compression failures apparently is weak in tension along the grain, presumably because the injured fibers are easily torn apart in tension. Therefore, if any compression failures are present on the tension side of a beam, that beam is likely to fail under a comparatively small load and, since compression failures extend across the grain, tension failures through them also extend across the grain, thereby giving the wood an appearance of being brash.

Figure 20, C, shows the brittle type of fracture in three specimens of Sitka spruce that had previously been compressed along the grain until the maximum load was reached and well-developed compression failures were visible. Figure 20, B, pictures one of the specimens after such compression. Figure 20, A, shows splintering fractures in matched specimens not previously compressed along the grain.

Since a beam almost always develops distinct compression failures on the compression side before it fails in tension, the final tension failure on the compression side follows an initial compression failure and is therefore an abrupt fracture, as is shown in the upper halves of the fractures in each of the specimens of Figure 20, A, thus causing the wood on that side to appear brittle. Splintering, therefore, occurs only on the tension side of a specimen, and the abrupt failure across the grain on the compression side of a beam is no criterion of the quality of the wood or of the presence of compression failures in the beam before the final load that caused failure was applied.

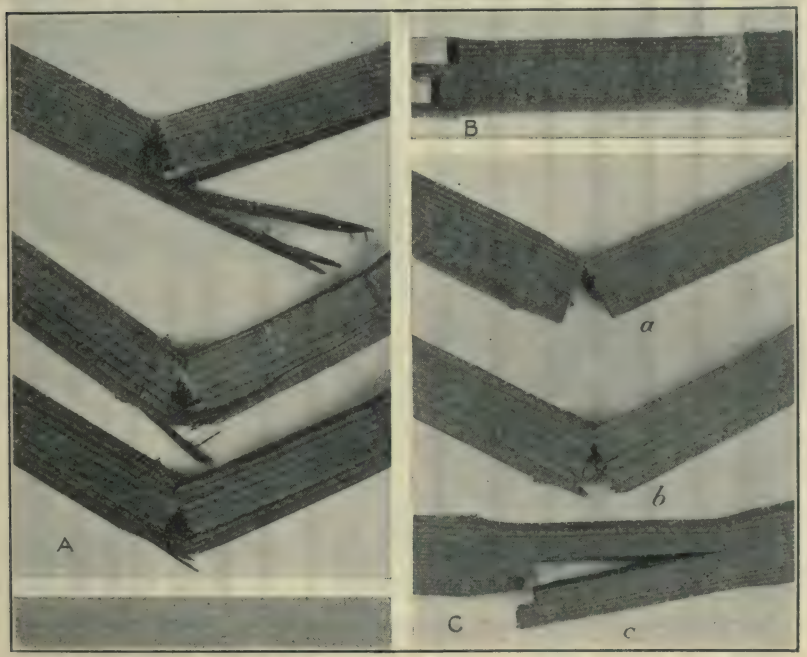


FIGURE 20.—The effect on the type of fracture, in bending tests, of preexistent compression failures in Sitka spruce: A, Specimens of normal wood matched with those of C; B, a typical compression failure caused purposely; C, fractures through compression failures previously caused purposely; *a*, specimen B after fracture; *b* and *c*, other specimens after fracture

Frequently at the Forest Products Laboratory abrupt fractures in beams have been traced to preexistent compression failures on the tension side, which were visible only with the microscope. (Fig. 21.) This type of compression failure is especially dangerous because of the difficulty of detecting it beforehand.

That compression failures are a frequent cause of brashness is shown for ash by Figure 5 and for Sitka spruce by Figure 6. Similarly preexistent compression failures were frequently found associated with low toughness values and brash failures in Douglas fir and oak. Some of these data are given in numerical terms in Table 6.

Further and more positive evidence of the effect of preexistent compression failures in reducing the toughness of wood is contained in Table 7, which gives the toughness value of the Sitka spruce specimens illustrated in Figure 20, A and C. The specimens previously compressed parallel to the grain gave toughness values only 40 per cent as high as those of matched specimens not so compressed; this value, of course, will vary with the degree of the previous failure in compression.

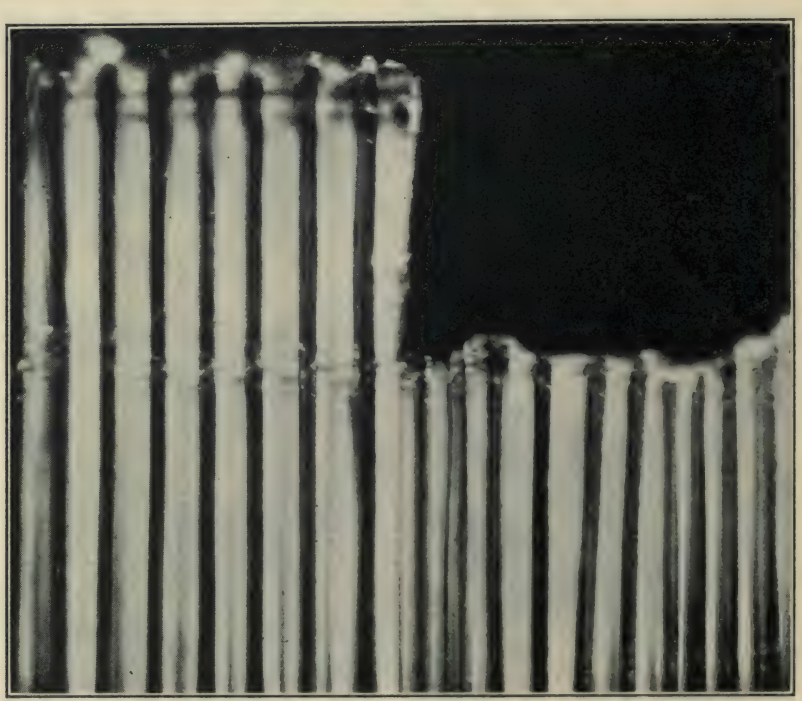


FIGURE 21.—Thin longitudinal section of fibers at a tension failure through a preexistent compression failure, which is indicated by the crosshatching in the fiber walls. The tension failure jumped from one compression failure to another. The photograph was taken by polarized light. × 210

TABLE 6.—*Percentages of specimens, low in toughness for their specific-gravity values, that failed through preexistent compression failures on the tension side, as indicated by visual inspection of the failures*

Species of wood and source	Classification of specimens	Specimens examined	Specimens failing in tension through preexistent compression failures	
		Number	*Number*	*Per cent*
Sitka spruce:				
Washington	Brash	36	17	47.2
Alaska	do	36	22	61.1
Oregon	20 per cent lowest in toughness for specific gravity.	176	119	67.6
Douglas fir, coast type	10 per cent lowest in toughness for specific gravity.	75	16	[1] 21.4
White ash	20 per cent lowest in toughness for specific gravity.	156	81	51.9

[1] The low percentage for the Douglas fir group was due to the presence of a relatively high percentage (33.3 per cent) of cross-grained specimens in that group.

TABLE 7.—*Average toughness of Sitka spruce specimens previously stressed to maximum load in compression parallel to the grain, and of matched specimens not so stressed*

Classification of specimens	Specimens examined	Average specific gravity [1]	Average moisture content	Average toughness	Type of failure
	Number		*Per cent*	*In.-lbs. per specimen* [2]	
Previously compressed	11	0.385	17.2	82.0	Abrupt.
Control	11	.383	16.4	203.8	Splintering.
Percentage relation of other values to control values.		100.5		40.2	

[1] Based on volume when air-dry and weight when oven-dry.
[2] Size of specimen, 5/8 by 5/8 by 16 inches.

White-ash specimens of a similar moisture content and similarly compressed to maximum load did not have abrupt fractures or low toughness values, presumably because the compression failures were much more minute and more scattered; a tough wood, like ash, characteristically develops numerous small compression failures, especially when it is not at a low moisture content, unless the compression is carried well beyond the maximum stress.

Usually when a beam is bent considerably beyond its elastic limit and is then turned around it will fail under a comparatively small load because of the compression failures, now on the tension side, formed in the first bending. This fact suggests that turning a board or ladder when it becomes bent in service is inadvisable. On the other hand, bending tests on tough hickory beams have shown that the beams could be bent in one direction till the maximum load was reached and then bent in the opposite direction without noticeable weakening.

Compression failures may be caused by excessive bending of trees by the wind or by snow loads, by the differences in inertia and in air resistance of the crown and the trunk below the crown when trees are felled, by felling trees over irregularities in the ground level, and by severe bending of timber products in their manufacture or use.

CROSS GRAIN

Under the designation cross grain is included spiral, diagonal, and interlocked grain, and such other local deviations of the grain from parallelism to the main axis of a stick as may be caused by wavy grain, curly grain, knots, and wounds.

Cross grain frequently is a cause of weakness in wood members, especially in bending, but it does not produce fractures characteristic of brash wood. Occasionally the grain may run almost directly across a stick, especially in pieces cut from the vicinity of knots. When broken in bending, such pieces may appear brash on superficial examination, yet careful inspection shows that the break was not across the grain but that the grain itself ran across the member.

HEIGHT IN TREE

No definite statement concerning the occurrence of brash wood at different heights of a tree can be made. The wood in the swelled

butts of ash and other species growing in very wet swamps is almost invariably brash. In trees growing under less moist conditions the wood in the butt usually is the toughest, but that fact does not necessarily mean that the wood higher up frequently is brash.

Compression wood usually is most abundantly developed in the lower part of the trunk, and therefore brashness from this cause would be expected to be more common in butt logs.

DISTANCE AND DIRECTION FROM CENTER OF TREE

Considerable variations in the weight and the strength of wood may occur in successive distances from the center of a tree, but no consistent generalization as to the relationship of toughness or brashness to the distance from the center can be made.

In conifers the wide-ringed wood frequently formed at the center and in both conifers and hardwoods the narrow-ringed wood found next to the bark of old, mature trees often is brash on account of its low density, already mentioned.

Compression failures apparently are of more common occurrence at the center of trees. Decay also, if present in tree trunks, is more common near the center, but numerous exceptions occur to all these generalizations.

No consistent or pronounced difference in the structure or the density of wood in different cardinal directions from the center of the tree has ever been noted, and therefore brash wood probably does not occur more commonly in one direction from the center than in another.

RATIO OF TENSILE TO COMPRESSIVE STRENGTH

The shock resistance, or toughness, of wood is dependent on the strength of wood in tension and in compression, upon the ratio between the two strength values, and upon the extent to which compression failures develop before failure takes place in tension. (P. 8.) Two pieces of wood may have the same strength in tension, but if one is weaker in compression it will bend farther before it breaks on account of the greater development of compression failures in it, although it will break under a smaller load. Since shock resistance is a measure of work absorbed, which in turn depends on the force exerted and the distance through which the force acts, it is entirely possible for a piece weak in compression to have greater shock resistance than one stronger in compression but of the same tensile strength.

To make satisfactory tests in tension along the grain of wood is exceedingly difficult, but compression tests can be made readily. To determine whether some of the brash specimens were relatively strong in compression, which would mean that their ratio of tensile to compressive strength would be comparatively high because they ranked low in toughness, compression-parallel-to-the-grain tests were made on short pieces cut from the toughness specimens of white oak and Sitka spruce. Table 8 shows the average values of maximum crushing strength obtained. In each instance the specimens designated as brash and low in toughness for their specific-gravity values had slightly lower average crushing strength than the matched tougher ones. This indicates that the brash specimens on an average must have been especially weak in tension along the grain.

TABLE 8.—*Maximum crushing strength along the grain and toughness values of brash and of tough oak, and of Sitka spruce low and high in toughness for its specific gravity*

Species of wood	Classification of specimens	Specimens tested	Average specific gravity [1]	Average toughness value	Average maximum crushing strength parallel to grain	Average moisture content of specimens tested in compression
		Number		*In.-lbs. per specimen* [2]	*Lbs. per sq. in.*	*Per cent*
Commercial white oak	Brash	51	0.656	124.1	9,128	6.1
	Tough	49	.655	339.9	10,044	5.9
Percentage relation of brash to tough.				100.2	36.5	90.9	
Sitka spruce	20 per cent lowest in toughness for specific gravity.	174	.390	48.4	5,917	9.7
	20 per cent highest in toughness for specific gravity.	177	.373	134.3	6,128	9.5
Percentage relation of low to high.				104.6	36.0	96.6	

[1] Based on volume when air-dry and weight when oven-dry.
[2] Size of specimen: White oak, ¾ by ¾ by 12 inches; Sitka spruce, 5/8 by 5/8 by 10 inches.

HIGH TEMPERATURE

Common opinion is that exposure to high temperatures, even if they are no higher than those maintained in commercial wood-drying kilns, may make wood brash. In order to determine the effect of fairly high temperatures on the manner of failure and certain strength properties of wood, Sitka spruce and white ash test specimens having a moisture content of 16 to 20 per cent were exposed to temperatures of 220° and 280° F. for from one to eight days and were then tested for toughness and maximum crushing strength along the grain. The results were compared with those for control specimens (*13*, *23*).

In the heated Sitka spruce specimens the type of failure was not appreciably different from that of matched control specimens even when the test pieces were heated to 280° F. and held at that temperature eight days. In the heated ash the type of failure also was not noticeably affected in test specimens heated to 220° and held there eight days or exposed to a temperature of 280° for one day, but those exposed to a temperature of 280° for two, four, or eight days failed with progressively less pronounced splintering than did the unheated specimens, although the fracture did not extend directly across the grain, as in a typically brash piece of wood, even after eight days of exposure to a temperature of 280°.

Of far more importance than the type of failure is the reduction in strength effected by high temperature. Table 9 gives the average toughness and maximum crushing strength parallel to the grain of groups of specimens subjected to high temperature; these values are expressed in terms of those of longitudinally matched control specimens. After the test specimens had been subjected to heat, all the pieces were stored under constant atmospheric conditions, which differed somewhat for the two species. The spruce control specimens came to a moisture content of 15.3 per cent and the ash controls to 10.4 per cent, while the heat-treated specimens reached

the values tabulated. These results indicate the effect of heat treatment in reducing the hygroscopicity of the wood; the reduction in moisture content caused by a temperature of 280° F. was approximately one-third for each species.

TABLE 9.—*Averages of certain physical and mechanical properties of Sitka spruce and white ash subjected to high temperature for different periods of time, expressed as percentages of the average values of matched control specimens*

Species of wood	Temperature employed										
	220° F.						280° F.				
	Time in heat chamber	Specimens tested [1]	Specific gravity [2]	Toughness	Maximum crushing strength parallel to grain [3]	Actual moisture content at time of test	Specimens tested [1]	Specific gravity [2]	Toughness	Maximum crushing strength parallel to grain [3]	Actual moisture content at time of test
	Days	*Number*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Number*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Sitka spruce	1	24	99.7	95.1	95.7	14.8	24	98.0	74.8	81.8	10.0
	2	24	100.0	89.8	89.6	14.3	24	98.4	69.5	74.6	10.6
	4	24	100.5	85.4	86.0	13.3	24	98.7	66.9	83.8	9.1
	8	24	99.7	76.9	85.0	13.2	24	94.9	51.2	74.8	9.7
White ash	1	24	100.0	91.4	106.4	7.7	24	98.8	36.8	110.0	5.5
	2	24	99.0	76.9	111.4	7.0	24	95.0	23.9	93.0	5.7
	4	24	98.6	73.4	108.6	8.4	24	94.2	30.3	78.8	7.0
	8	24	97.8	69.4	110.1	7.8	24	93.0	27.4	87.0	6.3

[1] A few individual toughness values were discarded in obtaining averages, because of defects in the test specimens.

[2] Based on volume at the moisture content at which the test was made and weight when oven dry.

[3] Adjusted by means of previously derived formulas to a moisture content of 15.3 per cent for Sitka spruce and 10.4 per cent for white ash, which were the average moisture-content values of the respective control groups. The difficulty of making accurate adjustments for moisture content may account for erratic values in this column.

Toughness usually decreased with increase in time of treatment and increase in temperature. Maximum crushing strength showed no such consistent relation between time of treatment and degree of temperature. The toughness of the spruce exposed for eight days to 280° F. was decreased to about one-half and the maximum crushing strength to about three-fourths that of the control specimens. For the ash the reduction was more than two-thirds and about one-eighth for these properties, respectively. In general, the heat-treated ash was reduced more in toughness and less in crushing strength than the spruce. The fact that the toughness was reduced more than the crushing strength of both species indicates that the tensile strength was affected considerably, the ratio of tensile to compressive strength thereby being brought closer to unity, particularly in the ash treated at 280°.

All these results, therefore, indicate that temperatures such as those usual in kiln-drying, which are below the 220° F. of one set of the tests, do not make wood brittle. Dry-kiln temperatures may weaken the wood slightly (*28*), but they do not cause it to break abruptly across the grain in bending. When abrupt fractures occur in wood as a result of exposure to extremely high temperatures it becomes darkened throughout so much and its odor changes to such an extent that the cause of brashness can be readily recognized.

CHEMICAL COMPOSITION

The chemical composition of wood does not vary a great deal within a species; in fact, the chemical differences between species lie principally in the materials deposited in the cell cavities and cell walls, especially in the heartwood. The basic materials, cellulose and lignin, from which the cell walls are made are nearly the same quantitatively in all woods. The probable effect of the slight differences in percentages of cellulose and lignin that have been observed in brash and in tough wood are masked by marked differences in the physical structure of the cell walls, which undoubtedly affect the mechanical properties a great deal. For example, spring wood, which is brash, has been found to contain a higher percentage of lignin than summer wood (*25*), and compression wood, which also is brash, likewise has a lignin content higher than that of normal wood as a whole (*7*, *12*). From these facts alone it might be inferred that lignin reduces the toughness of wood were it not for the additional fact that the structure of the more highly lignified wood, in these instances, is such as to leave little doubt that structure is the cause of the brashness.

In the study of brashness in oak the ash content was determined for 50 brash and 49 tough specimens of the same average specific gravity, to see if either group contained enough mineral matter to affect its weight or its strength appreciably. On on average the ash content of the brash specimens was 0.60 per cent and that of the tough ones 0.34 per cent of the weight of the wood when oven dry. The high average for the brash group was due primarily to 7 specimens in which the ash content ranged from 1.1 to 1.8 per cent. These 7 specimens contained an average of only 8.9 per cent wood fiber, whereas the average percentage of wood fiber for the remaining 43 brash specimens was 19.3 and that for all the tough specimens 28.4 per cent. The corresponding average toughness values were 87.0 inch-pounds per specimen for the 7 brash pieces having high ash content, 130.7 for the remaining 43 brash ones, and 339.9 for all the tough ones.

The cell wall is the only place in which mineral matter would be expected to affect the strength of the wood. A microscopic examination of the specimens having a high ash content showed that in most of them crystals were noticeably abundant in the ray and the wood parenchyma cell cavities, in which location they could hardly cause brashness. Evidently the high ash content of certain specimens was associated with other factors, brought about by growth conditions, that made the wood brash.

Materials deposited in the cell wall, on the other hand, may increase certain strength properties of wood to a greater extent than the weight. Tests of sapwood and of both leached and unleached heartwood of such woods as redwood, western red cedar, and black locust, which contain an appreciable amount of water-soluble extractives in the heartwood much of which is undoubtedly deposited in the cell wall, indicate that the infiltrated materials are responsible for the fact that certain strength properties of these species are greater than their weights indicate (*15*). Shock resistance is affected the least, whereas strength in compression is affected the most by the presence or removal of extractable materials.

DECAY

Decay in wood is a well-known cause of brashness. In extreme instances it reduces strength so much that the wood can be crushed with the fingers.

Figure 22, A, shows an abrupt fracture in the lower front edge of a red oak specimen tested in static bending. Advanced decay in that portion of the stick caused this type of fracture, which is in contrast with the typical splintering of the rest of the fracture. Not always, however, does decay-infected wood break so abruptly across the grain;

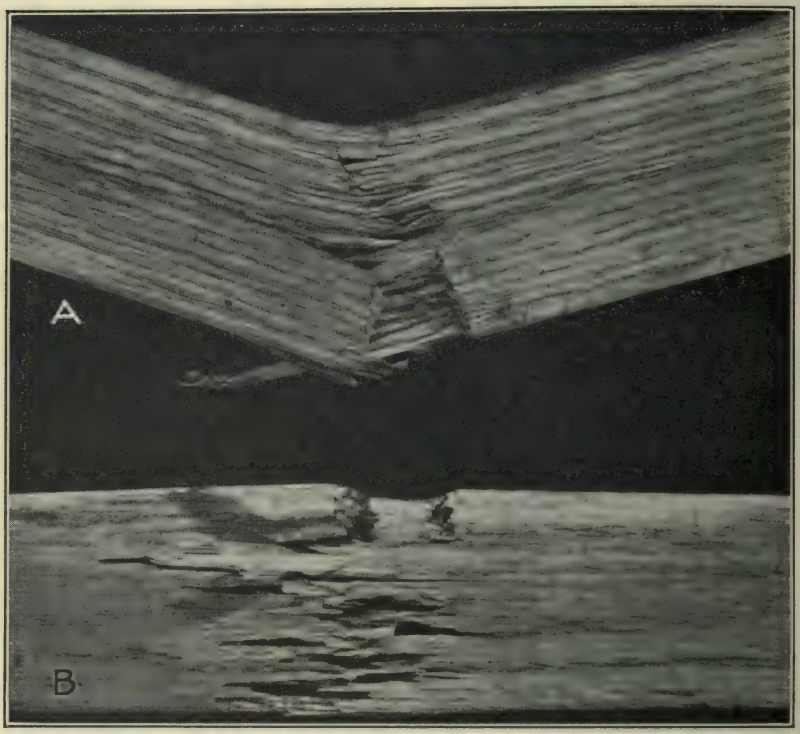


FIGURE 22.—Red oak, fractured in bending, with splintering in the sound wood and an abrupt break through the decay-infected wood in the lower front portion of the specimen: A, Side view; B, bottom view

the effect of decay on the kind of fracture depends on the particular species of fungus causing the decay and on its stage of development.

In the early stages of decay toughness is the property most reduced, although in advanced stages all mechanical properties drop off rapidly. Compression parallel to the grain is affected much less than toughness, especially in the early stages, which again indicates that the tensile strength is greatly reduced.

Because of the known effects of decay on the strength of wood, every piece that is decay infected, even to a slight degree, should be regarded with suspicion. Different kinds of wood-destroying fungi attack wood differently, so that no simple rules for the recognition of decay in its early stages can be laid down. In diagnosing decay in wood by means of discoloration the publications of Boyce (*4*) and of Hubert (*11*) are among those of value (*27*).

SUMMARY

Brashness is an abnormal condition that causes wood, in bending, to break suddenly and completely across the grain when deflected only a small amount; in consequence the piece absorbs little energy or work.

Abrupt and complete failure is an objectionable characteristic under both static and suddenly applied loads, because it does not give warning, as a splintering failure does; the small amount of energy absorbed is especially objectionable under the shock, in which the work involved in bending is an important factor in preventing complete failure of beams.

Wood may be brash as a result of adverse conditions during growth or of the action of extrinsic agencies after growth. It may be relatively weak in various mechanical properties without showing abrupt fractures when broken in bending, but when abrupt fractures do occur in wood they show that its shock resistance, at least, is below normal, although it may be more nearly normal in other mechanical properties.

The following are the principal factors responsible for brashness in wood. Recognition of these factors is important in the detection of brash wood before failure. There is, however, no sharp line of demarcation between brash and tough wood. The degree of refinement to be used in culling brash wood depends on the value of the material and the service for which it is intended.

Wood low in density for its species almost invariably is brash, especially when dry. This is due to the smaller amount of wood substance in such wood and to the greater slope with respect to the cell axes of the fibrils in the walls of the cells in the predominating tissues. Low density is usually associated with very narrow growth rings (slow growth) in timber of any species, with very wide rings (fast growth) in softwoods, and with swelled butts of trees growing in very wet swamps. No sharp lines as to density (or specific gravity) or width of rings can be drawn between brash and tough wood, however, since the two kinds of wood merge imperceptibly. Species of wood that are normally low in density are not characteristically brash, although they are relatively weak.

In some oak the wood fibers are comparatively few in number, other tissues that do not contribute so much to strength having taken their place. Since these tissues, together with their cell contents, are not necessarily much lower in weight than the empty wood fibers that they replace, a piece weak for this cause may nevertheless be as heavy as a normal piece.

Compression wood is wide-ringed wood having a relatively large percentage of summer wood which, however, is not so dense as normal summer wood. It is formed on the lower side of leaning trees of all softwood, but not of hardwood, species. Compression wood is brittle and, when dry, usually ranks low in toughness and some other strength properties. On account of its brittleness, erratic strength properties, excessive longitudinal shrinkage, and tendency to warp, it should be excluded from all uses in which such characteristics are objectionable.

Wood subjected to either severe bending or end compression develops compression failures in the fiber walls, the failures extending

more or less directly across the grain. Fibers so distorted fail relatively easily in tension along the grain, and when on the tension side of a beam they not only cause early failure under stress but also, since the existing compression failures extend across the grain, cause abrupt fractures on the tension side. A fracture is always abrupt on the compression side because of the compression failures that develop in bending.

Compression failures, if well developed, can readily be seen on the surface of lumber or timber, especially when the pieces have been planed. On the other hand, compression failures are sometimes so minute that, outside of a microscopical examination, their presence can be detected only by the abrupt fractures produced in bending either the piece in question or small test sticks cut from it.

Prolonged high temperature may make wood brash, but temperatures such as those ordinarily maintained in commercial dry kilns do not cause abrupt fractures in wood, although the strength of the wood may be reduced thereby. The indications are that abrupt fractures are not produced by heat unless a temperature high enough to darken the wood throughout is used.

Decay in wood is a well-known cause of brashness. Shock resistance is the first mechanical property affected by the progressive disintegration of wood by fungi. Wood may show a reduction in this property even before the decay has advanced far enough to be readily recognized by inspection or before the type of fracture is affected by it. No wood, therefore, that shows the slightest signs of infection by decay should be used where a high degree of toughness is required.

LITERATURE CITED

(1) ADAMS, W. R., JR.
1928. STUDIES IN TOLERANCE OF NEW ENGLAND FOREST TREES. VIII. EFFECT OF SPACING IN A JACK PINE PLANTATION. Vt. Agr. Expt. Sta. Bul. 282, [55] p., illus.

(2) AMERICAN SOCIETY FOR TESTING MATERIALS.
1930. STANDARD METHODS OF TESTING SMALL CLEAR SPECIMENS OF TIMBER. SERIAL DESIGNATION D143–27. Amer. Soc. Testing Materials Standards . . . 1930. (Pt. 2, Non-Metallic Materials) : 818–854. illus.

(3) BIENFAIT, J. L.
1926. RELATION OF THE MANNER OF FAILURE TO THE STRUCTURE OF WOOD UNDER COMPRESSION PARALLEL TO THE GRAIN. Jour. Agr. Research 33 : 183–194, illus.

(4) BOYCE, J. S.
1923. DECAYS AND DISCOLORATIONS IN AIRPLANE WOODS. U. S. Dept. Agr. Bul. 1128, 52 p., illus.

(5) BRUSH, W. D.
1913. A MICROSCOPIC STUDY OF THE MECHANICAL FAILURE OF WOOD. U. S. Dept. Agr., Forest Serv. Rev. Forest Serv. Invest. 2 : 33–38. illus.

(6) CLARK, G. L.
1930. CELLULOSE AS IT IS COMPLETELY REVEALED BY X RAYS. SPECIAL APPLICATION TO THE GROWTH AND CLASSIFICATION OF COTTON, THE STRUCTURE OF WOOD, AND THE MANUFACTURE OF RAYON. Indus. and Engin. Chem. 22 : 474–487, illus.

(7) DADSWELL, H. E., and HAWLEY, L. F.
1929. CHEMICAL COMPOSITION OF WOOD IN RELATION TO PHYSICAL CHARACTERISTICS. A PRELIMINARY STUDY. Indus. and Engin. Chem. 21 : 973–975.

(8) FORSAITH, C. C.
1921. MORPHOLOGY OF WOOD IN RELATION TO BRASHNESS. Jour. Forestry 19 : 237–249, illus.

(9) FREY, A.
1926. DIE SUBMIKROSKOPISCHE STRUKTUR DER ZELLMEMBRANEN. EINE POLARISATIONSOPTISCHE STUDIE ZUM NACHWEIS DER RICHTIGKEIT DER MIZELLARTHEORIE. Jahr. Wiss. Bot. 65: [195]–223, illus.
(10) GERRY, E.
1915. FIBER MEASUREMENT STUDIES; LENGTH VARIATIONS: WHERE THEY OCCUR AND THEIR RELATION TO THE STRENGTH AND USES OF WOOD. Science (n. s.) 41: 179.
(11) HUBERT, E. E.
1924. THE DIAGNOSIS OF DECAY IN WOOD. Jour. Agr. Research 29: 523–567, illus.
(12) JOHNSEN, B., and HOVEY, R. W.
1918. THE DETERMINATION OF CELLULOSE IN WOOD. Jour. Soc. Chem. Indus. 37: 132T–137T, illus.
(13) KOEHLER, A., and PILLOW, M. Y.
1925. EFFECT OF HIGH TEMPERATURES ON MODE OF FRACTURE OF A SOFTWOOD. South. Lumberman 121 (1576): 219–221, illus.
(14) LODEWICK, J. E.
1930. EFFECT OF CERTAIN CLIMATIC FACTORS ON THE DIAMETER GROWTH OF LONGLEAF PINE IN WESTERN FLORIDA. Jour. Agr. Research 41: 349–363, illus.
(15) LUXFORD, R. F.
1931. EFFECT OF EXTRACTIVES ON THE STRENGTH OF WOOD. Jour. Agr. Research 42: 801–826, illus.
(16) MARKWARDT, L. J.
1930. AIRCRAFT WOODS; THEIR PROPERTIES, SELECTION, AND CHARACTERISTICS. Natl. Advisory Com. for Aeronautics Rpt. 354, 34 p., illus.
(17) ———
1930. COMPARATIVE STRENGTH PROPERTIES OF WOODS GROWN IN THE UNITED STATES. U. S. Dept. Agr. Tech. Bul. 158, 39 p.
(18) NEWLIN, J. A., and WILSON, T. R. C.
1917. MECHANICAL PROPERTIES OF WOODS GROWN IN THE UNITED STATES. U. S. Dept. Agr. Bul. 556, 47 p., illus.
(19) ——— and WILSON, T. R. C.
1919. THE RELATION OF THE SHRINKAGE AND STRENGTH PROPERTIES OF WOOD TO ITS SPECIFIC GRAVITY. U. S. Dept. Agr. Bul. 676, 35 p., illus.
(20) PAUL, B. H.
1926. HOW GROWTH AFFECTS QUALITY IN HICKORY AND ASH. Wood Working Indus. 2 (2): 28–30, illus.
(21) ———
1930. THE APPLICATION OF SILVICULTURE IN CONTROLLING THE SPECIFIC GRAVITY OF WOOD. U. S. Dept. Agr. Tech. Bul. 168, 20 p., illus.
(22) ——— and MARTS, R. O.
1931. CONTROLLING THE PROPORTION OF SUMMERWOOD IN LONGLEAF PINE. Jour. Forestry 29: 784–796, illus.
(23) PILLOW, M. Y.
1929. EFFECT OF HIGH TEMPERATURES ON THE MODE OF FRACTURE AND OTHER PROPERTIES OF A HARDWOOD. Wood Working Indus. 6 (4): 8–9, 30, illus.
(24) RITTER, G. J.
1930. WOOD FIBERS. Jour. Forestry 28: 533–541, illus.
(25) ——— and FLECK, L. C.
1926. CHEMISTRY OF WOOD. IX—SPRINGWOOD AND SUMMERWOOD. Indus. and Engin. Chem. 18: 608–609.
(26) ROBINSON, W.
1920. THE MICROSCOPICAL FEATURES OF MECHANICAL STRAINS IN TIMBER AND THE BEARING OF THESE ON THE STRUCTURE OF THE CELL-WALL IN PLANTS. Roy. Soc. [London], Phil. Trans. Ser. B 210: 49–82, illus.
(27) UNITED STATES DEPARTMENT OF AGRICULTURE, FOREST SERVICE, FOREST PRODUCTS LABORATORY.
1928–[29]. MANUAL FOR THE INSPECTION OF AIRCRAFT WOOD AND GLUE FOR THE UNITED STATES NAVY. 152 p., illus. Washington.
(28) WILSON, T. R. C.
1920. THE EFFECT OF KILN DRYING ON THE STRENGTH OF AIRPLANE WOODS. Natl. Advisory Com. for Aeronautics Rpt. 68. 69 p., illus.
(29) ZON, R., and AVERELL, J. L.
1928. THE EFFECT OF DRAINAGE ON FOREST GROWTH. Agr. Engin. 9: 171–173, illus.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Forest Service	R. Y. STUART, *Chief.*
Branch of Research	EARLE H. CLAPP, *Assistant Forester, in Charge.*
Forest Products Laboratory	CARLILE P. WINSLOW, *Director.*
Section of Silvicultural Relations.	ARTHUR KOEHLER, *Principal Xylotomist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 341 FEBRUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

EFFECTS OF CERTAIN ENVIRONMENTAL FACTORS ON STRIPE DISEASE OF BARLEY AND THE CONTROL OF THE DISEASE BY SEED TREATMENT [1]

By R. W. LEUKEL, *Associate Pathologist, Division of Cereal Crops and Diseases;* J. G. DICKSON, *Professor of Plant Pathology, Wisconsin Agricultural Experiment Station,* and *Agent, Division of Cereal Crops and Diseases;* and A. G. JOHNSON, *Principal Pathologist, Division of Cereal Crops and Diseases, Bureau of Plant Industry*

In Cooperation with the Wisconsin Agricultural Experiment Station

CONTENTS

	Page
Introduction	1
Nature of the disease	2
Time and manner of inoculation	4
Location of the fungus in the seed	4
Longevity of conidia and seed-borne mycelium	5
Viability of seed from diseased plants	6
Secondary infection	6
Effect of environmental conditions	7
Soil fertility	7
Soil temperature and moisture	7
Control of stripe disease by seed treatment	14
Experiments in 1926	16
Experiments in 1927	17
Experiments in 1928	25
Experiments in 1929	28
Experiments in 1930	31
Discussion	34
Summary	36
Literature cited	37

INTRODUCTION

Stripe disease of barley, caused by *Helminthosporium gramineum* Rabh., occurs in nearly all countries where barley is extensively grown. It varies in severity from a mere trace to as much as 75 per cent infection. Drechsler (*4*) [2] reviewed the reports of its occurrence up to 1922 in the following countries: Sweden, Denmark, Germany, Netherlands, England, Ireland, Russia, United States, Canada, Argentina, Japan, China, and India. A report from Scotland (*1*) states that in 1919 the disease was present to some extent in nearly every barley field in Scotland, especially in the 4-row and 6-row varieties.

In 1923 Gram and Rostrup (*10*) reported its general occurrence in Denmark, but Gram and Thomsen (*11*), in 1925, and Gram, Jørgensen,

[1] The investigations here reported were conducted by the Division of Cereal Crops and Diseases, Bureau of Plant Industry, in cooperation with the plant pathology department of the Wisconsin Agricultural Experiment Station.

[2] Italic numbers in parentheses refer to Literature Cited, p. 37.

and Rostrup (*9*), in 1928, stated that it was declining in intensity in Denmark as a result of the widespread practice of seed treatment. Wahl (*39*) reported that stripe disease was severe in Austria in 1925. Porter [3] stated in 1926 that it was prevalent in eastern China.

Dorph-Petersen (*3*) observed in 1926 that out of 500 barley fields in Zeeland (Netherlands) about 50 per cent showed infection. Novák (*24*) reported in 1926 that stripe disease was of considerable economic importance in Czechoslovakia.

Numerous references to the occurrence of stripe disease are found in German literature. According to Gisevius and Straib (*8*), heavy infection was observed for a number of years in the Hessian Ried, while in Rhemhessen, a region of extensive barley cultivation, the disease was less in evidence.

The occurrence of stripe disease in Russia was mentioned by Geschele (*7*), in Tunis by Chabrolin (*2*), and in Japan by Nisikado (*22*). Smith and Rattray (*36*) mention the wide distribution of stripe disease as well as net blotch and spot blotch in South Africa.

While on trips to various countries of Europe and western Asia in 1930 one of the writers (Dickson) made observations on the occurrence of barley stripe disease at various points. The disease was found to be more prevalent in the northern sections of Europe. In the spring-barley sections of the countries along the Baltic Sea and in northern Russia barley stripe disease was considered of major importance. Southward it was much less prevalent except at the higher elevations, as, for example, in the Transcaucasian and Armenian Mountains, where barley was heavily infected with stripe disease at the higher elevations, yet only a trace of the disease was found at the lower elevations, even in the winter-barley sections. The same condition was found in the Balkan States of south-central Europe. The distribution of the disease seemed to be correlated with and largely determined by regional conditions, especially of temperature and moisture.

H. V. Harlan,[4] of the Bureau of Plant Industry, states that he found stripe disease of economic importance in the various dry-land farming sections along the Mediterranean Sea in western Egypt. He observed very little of the disease in the irrigated sections of Egypt, hardly any in Kashmir, and on the high plateau of Ethiopia it was entirely absent.

As reported by some of the workers previously cited, losses due to stripe disease may, at times, amount to more than 50 per cent. Although losses as severe as this are not common, losses of from 10 to 25 per cent are of frequent occurrence and emphasize the importance of preventing the disease by means of effective seed treatments or the development of immune or highly resistant varieties. Progress in this direction, of course, is aided considerably by a general knowledge of the facts concerning the life cycle of the causal organism and the conditions that favor or inhibit the development of the disease.

NATURE OF THE DISEASE

The fungus that causes the stripe disease of barley was first described by Rabenhorst, in 1857, as *Helminthosporium gramineum.*

[3] PORTER, R. H. A PRELIMINARY REPORT OF SURVEYS FOR PLANT DISEASES IN EAST CHINA. U. S. Dept. Agr., Bur. Plant Indus. Plant Disease Rptr. Sup. 46:153–166. 1926. [Mimeographed.]

[4] In correspondence.

The contributions of various early workers to the general knowledge of this disease and its causal organism are reviewed by Ravn (*28*), who did considerable research work in this field and definitely distinguished stripe disease from what is known in the United States as net blotch caused by *H. teres* Sacc. (*Pyrenophora teres*). The failure of some of the earlier writers to distinguish definitely between these two barley diseases is ably discussed by Ravn (*28*) and by Drechsler (*4*). The latter writer also gives an excellent description of the symptoms of both diseases and of the causal organisms.

Ravn's (*28*) view, that the life cycle of the stripe-disease fungus is analogous to that of some of the cereal smuts, has been generally accepted until a relatively recent time. The conidia from sporulating lesions on the leaves of diseased plants, according to Ravn, are carried to the heads of healthy plants, where they either infect the embryo or become lodged between the glume and the pericarp of the seed. In the latter case they germinate there and form a mycelial web, which, in a latent condition, carries over the fungus until the seed germinates. At this time the mycelium revives, infects the embryo and eventually the shoots, and keeps pace with the growing points of the infected culms. The leaves and leaf sheaths, according to Ravn, become infected by means of the fungus growing out from the culm. The spores from the lesions on the leaves, of course, are carried to the healthy heads of that crop, and thus the life cycle is completed.

Smith (*35*) maintains that the coleoptile is the first organ to become infected, that infection proceeds from the inner side of the coleoptile to the first leaf and thus successively from each leaf to the next emerging leaf and from the leaves to the pith of the stems, and that invasion of the growing point results in speedy death of the culm. Furthermore, according to Smith, the mycelium that invades the head of the diseased culm comes from the sheathing base of the uppermost leaf and not from the stem. This is evident, he states, from the fact that—

> the diseased areas on the chaffs of the newly emerged ear are precisely those upper and dorsal parts which were in contact with the diseased parts of the enwrapping sheath, not the embryonic ends which are tucked in toward the rachis.

He bases his conclusions on a histological study of microtome sections as well as on observations on growing plants. The somewhat earlier results obtained by Vogt (*38*) agree in the main with those of Smith. Johnson (*14*) also suggested that in view of the fact that germinating seed can be successfully inoculated without removing the hulls, infection may take place through the coleoptile.

In experiments with Wisconsin Pedigree No. 5 barley, which was infected with loose and covered smuts as well as with stripe disease, it was occasionally observed that rather vigorous but stripe-diseased plants produced heads entirely affected with either loose or covered smuts. This could be interpreted to favor Smith's view, if it may be assumed that the stripe-disease fungus would not harmoniously share the growing point of a culm with either of these smut fungi.

In regard to various other phases of stripe disease, the results obtained or the views expressed by investigators frequently differ. A brief review of some of these follows.

TIME AND MANNER OF INOCULATION

Investigators in general agree that the heads, and therefore the kernels, of healthy plants receive their inoculum in the form of conidia borne primarily by the wind from leaves of diseased plants. Some of the earlier workers believed that flower infection occurred after the manner of loose smut of wheat. At present, however, the generally accepted view is that the conidia lodge near the awn end of the glume, where, under favorable conditions, they germinate, giving rise to a mycelial growth between the glume and the pericarp. This mycelium, in a latent state, is generally conceded to be the main factor in carrying the disease over from one crop to another. Investigators are not entirely agreed, however, as to the time during which head inoculation takes place. Genau (*6*), for example, states that inoculation of barley flowers with conidial suspension was most successful the day after they opened. He thinks the time for effective inoculation is limited to the blossoming period. Winkelman (*40*), however, using a different method, secured infection by inoculating the kernels at different periods after flowering time. He believes that even if the spores adhere to the outside of the glume, they may germinate there under favorable moisture conditions, the fungus may penetrate the glume, and the mycelium may spread between the glume and pericarp. Inasmuch as infection of the plants can be brought about by applying mycelium or spores to the outside of the seeds at the time of sowing, it seems reasonable to suppose that inoculation of the kernels of healthy plants in the field may occur for a considerable period. It probably is contingent, to some extent, on suitable conditions of atmospheric moisture and temperature.

LOCATION OF THE FUNGUS IN THE SEED

As may be gathered from the previous paragraph, the consensus of opinion is that the chief agent in carrying the fungus in the seed is the dormant mycelium between the glume and the pericarp. The fact that the disease can be controlled easily by seed treatments other than the hot-water treatment seems to dispose of the probability of mycelium in the embryo, although Ravn (*28*) contends that the embryo may harbor the fungus. The work of Winkelman (*40*), Johnson (*14*), and others suggests that conidia borne on the outside of the kernel may, under favorable conditions, carry over the disease; (although Smith (*35*) considers the possibility of infection from this source very slight, as does also Fuchs (*5*)). Kiessling (*15*) and Van Poeteren (*26*) claim that they found perithecia of the perfect stage of the fungus on the glumes of barley, and Vogt (*38*) states that the black sclerotia on the stubble of diseased plants in the fall develop into perithecia of *Pleospora gramineum*. Genau (*6*) claims that he used ascospores successfully in inoculating plants. However, it does not seem to be generally believed that ascospores play an important rôle as inoculum for stripe disease.

The mycelium that develops beneath the glume evidently penetrates the pericarp to some extent, as is evidenced by the fact that removing the glumes from seeds causes little or no reduction in the percentage of infected plants. From the two seed lots, Fuchs (*5*) obtained, respectively, 32.4 and 4.5 per cent of stripe-diseased plants from seed with the hulls removed and 32.3 and 4.5 per cent from

normal seed. In a similar experiment, the data for which are shown in Table 1, the writers obtained an average of 17.1 per cent of infection from normal seed, 15 per cent from hulled seed, and 17.1 per cent when the removed hulls were sown with the hulled seed.

TABLE 1.—*Stripe disease in Wisconsin Pedigree No. 5 barley grown in the field from three lots of seed: (1) Hulls not removed; (2) hulls removed; (3) hulls removed but sown with the seed; Arlington Experiment Farm, Rosslyn, Va., 1929–30*

Replication No.	Results from seeds with—								
	Hulls not removed; total plants			Hulls removed; total plants			Removed hulls sown with seed; total plants		
	Grown	Infected		Grown	Infected		Grown	Infected	
	Number	*Number*	*Per cent*	*Number*	*Number*	*Per cent*	*Number*	*Number*	*Per cent*
1	82	19	23.2	46	3	6.5	55	8	14.5
2	84	12	14.3	54	10	18.5	53	13	24.5
3	78	13	16.6	57	12	21.1	49	7	14.3
4	90	13	14.4	56	7	12.5	71	11	15.5
Total	334	57	17.1	213	32	15.0	228	39	17.1

Vogt (*38*) states that the hyphae of the resting mycelium traverse the cells of the inner epidermis of the glume and the outer cell layer of the pericarp. Mycelium was not detected in the interior of the endosperm or in any part of the embryo. He further states that microscopic evidence proves that the mycelium in the pericarp is primarily, if not exclusively, the agent that transmits the disease.

LONGEVITY OF CONIDIA AND SEED-BORNE MYCELIUM

There is some diversity of opinion regarding the length of time during which the conidia of *Helminthosporium gramineum* remain viable. Genau (*6*) obtained no germination after three and one-half months. Winkelman (*40*) secured germination of conidia eight months old. Ravn (*28*) states that spores eight months old germinated sparingly. Fuchs (*5*) obtained excellent germination for 9 months, after which the viability declined rapidly, so that after 17 months only 5 per cent of the spores germinated. Isenbeck (*13*) secured 90 per cent germination after 12 months and 20 per cent after 34 months, the spore material being held at a temperature below 5° C. Spores taken from dried barley leaves kept in the laboratory at the Arlington Experiment Farm, Rosslyn, Va. (near Washington, D. C.), failed to show any signs of germination after four months. Doubtless the longevity of the conidia depends upon conditions of temperature and humidity during the period of storage. Since there appears to be some evidence that conidia on the outside of the kernel may perpetuate the disease under certain conditions, it follows that the length of the period during which and the conditions under which they remain viable may be of some importance in this respect.

Here again may be pointed out the greater importance of the seed-borne dormant mycelium in the perpetuation of the disease. Ravn (*28*) found abundant stripe disease in 1898 in plants grown from seed harvested in 1896. Genau (*6*) states that he found the mycelium

in grain viable after two years, and Smith (*35*) reports similar results. In 1927 the writers found over 7 per cent of stripe disease in barley grown from seed raised in 1922, indicating that a 5-year period failed to kill the seed-borne mycelium.

VIABILITY OF SEED FROM DISEASED PLANTS

Conflicting statements have been made by different investigators about the extent to which stripe-diseased plants may produce viable seeds and whether such seeds necessarily give rise to infected plants. Most of the investigators, in describing stripe-diseased plants, state that the heads may form kernels but that these usually are sterile. Ravn (*28*) found that of 200 kernels from infected plants only 2 germinated. Drechsler (*4*) states that the ovaries in the heads of diseased plants rarely develop anything beyond abortive seeds and that viable seeds are not generally produced. Novák (*23*), on the contrary, states that 300 seeds taken from infected plants and sown in the greenhouse produced healthy plants. However, it does not necessarily follow that none of these kernels carried the fungus. Novák does not state at what temperature the greenhouse was maintained, and it is easily possible that a relatively high temperature (25° C., for example) during the period of germination may have enabled the seedlings to escape infection, as frequently is the case.

In July, 1927, stripe-diseased plants of Minsturdi and Wisconsin Pedigree No. 6 barley were collected at Madison, Wis., and stored in the laboratory at the Arlington Experiment Farm. On January 14, 1929, a number of heads of each variety were selected, the kernels were carefully threshed out by hand, and the better-developed ones were sown in a greenhouse kept at a temperature of 15° C. Of 50 kernels of the Minsturdi barley sown, only 5 germinated, and the plants that developed were free from stripe disease. Of 100 kernels of Wisconsin Pedigree No. 6, 17 germinated, and only 4 plants showed stripe-disease infection.

Two years later, on February 5, 1931, 50 heads were selected at random from this same lot of diseased plants of Wisconsin Pedigree No. 6 barley collected in 1927. The heads were carefully hand threshed, and 615 seeds were obtained, most of which apparently were abortive. Nevertheless, all of them were placed in a germinator kept at a temperature of 25° C., along with 100 normal kernels of this same variety grown in 1925 and then 6 years old. Of the normal kernels 54 per cent germinated. None of the kernels from the 50 diseased heads showed any indication of viability, although two years before some of the kernels from this lot of material had germinated. Evidently storage for 37 months under conditions obtaining in the laboratory cupboard was sufficient to destroy what viability any of these seeds may once have had.

SECONDARY INFECTION

Secondary infection by spores of *Helminthosporium gramineum* on leaves of barley probably is not common in nature. Ravn (*28*), using mycelium, obtained infection in 39 per cent of his trials. The writers made parallel inoculations on young barley leaves in the greenhouse with spores of *H. gramineum* and *H. teres*. Freshly collected spores of both species were applied to barley leaves, after which

the plants were placed in a moist chamber for 48 hours. After 12 days all the leaves inoculated with spores of *H. teres* were abundantly infected and showed the characteristic netting which is the outward manifestation of net blotch. The leaves inoculated with spores of *H. gramineum*, however, showed only slight indications of local infection, and these were not characteristic of stripe disease. In view of these results it seems highly improbable that any appreciable amount of secondary infection by *H. gramineum* occurs in the field even under the most favorable natural conditions.

EFFECT OF ENVIRONMENTAL CONDITIONS

SOIL FERTILITY

Ravn (*28*) states that he observed no effect of manure on the incidence of stripe disease, although he cites Rostrup's results in which the latter had observed 13 per cent of stripe disease where nitrogen fertilizers had been used and only 5 to 7 per cent where none had been applied. Plaut (*25*) found that neither manure nor fertilizers had any effect on the amount of stripe disease in the crop. Rippel and Ludwig (*31*), on the other hand, report that stripe disease is inhibited by increased soil fertility and that the disease develops most abundantly in the more poorly fertilized soil. Smith (*35*) also states that any condition favorable for the plant, such as abundant soil fertility, tends to make it grow away from the disease. The writers are, to some extent, inclined to agree with this latter view. While no experiments were made along this line, it often has been observed that in rows where the plants, on the whole, were more or less stunted and lacking in vigor, owing to poor fertility, the percentage of stripe-diseased plants invariably was greater than where vegetative growth was more vigorous because of more fertile soil.

Some observations have been made also on the relation between soil type and stripe disease. Riehm (*30*) refers to an instance in which seed sown in marshy soil produced a healthy crop; in another case, seed sown in light soil produced a stripe-diseased crop. This would be in agreement with the theory that high fertility tends to inhibit stripe-disease development, it being assumed that the marshy soil is the more fertile. Kiessling (*15*), on the contrary, makes the statement that the disease was favored by damp black soil.

SOIL TEMPERATURE AND MOISTURE

Most investigators who have studied the physiology of stripe-disease infection mention the fact that when naturally inoculated seed is sown the development of the disease is favored by the prevalence of a relatively low soil temperature during the period immediately after the seed is sown and before the seedlings emerge. Most of them draw their conclusions from field observations, while a few rely upon data secured from experiments in which soil temperature was a controlled factor. All are not in exact agreement regarding the optimum soil temperature for stripe-disease development, but it is placed below 20° C. and usually above 10°. These differences of opinion may be accounted for by concurrent differences in soil moisture, which also seem to be a factor influencing infection, or by the fact that the investigators may have been dealing with different physiologic forms.

Johnson (*14*) distinguished between two physiologic forms of *Helminthosporium gramineum* by means of differences in temperature requirements when these different strains were grown in pure culture. Isenbeck (*13*) suggests the existence of three physiologic forms, based on their differences when grown in pure culture and also on differences in results obtained in inoculation experiments.

Numerous field observations prior to 1922 had convinced the writers of the importance of soil temperature as a factor in the development of stripe disease. In the fall of 1922, experiments were begun to determine, within rather wide limits, the cardinal temperatures for the development of stripe disease in plants grown from naturally inoculated seed. A study of the relation of soil moisture to the development of stripe disease was included.

In most of these experiments the plants were grown to the second-leaf or third-leaf stage in metal cans suspended in tanks containing water, the temperature of which was automatically controlled. The equipment used has been described previously (*16*).

The first experiment was somewhat preliminary in nature and was intended primarily to try out the equipment. Seed of Wisconsin Pedigree No. 6 barley (crop of 1922) was sown in soil at each of six temperatures. The results were not very striking, as there was little difference in the amount of infection secured at 10°, 15°, and 20° C. (Table 2, series 1.) The small number of plants grown and the fact that they were allowed to mature in the cans, thus preventing normal development, make these results, on the whole, rather unimportant.

TABLE 2.—*Effect of soil temperature on development of stripe disease in Wisconsin Pedigree No. 6 barley grown from naturally inoculated seed in controlled soil-temperature tanks in the greenhouse, Arlington Experiment Farm, Rosslyn, Va.*

Series	Temperature of soil	Days before emergence	Seeds sown	Plants grown	Plants infected	
	° C.	*Number*	*Number*	*Number*	*Number*	*Per cent*
1	10		60	57	5	8.8
	15		60	47	4	8.5
	20		45	39	3	7.7
	24		60	49	1	2.0
	28		60	53	0	0
	32		60	51	0	0
2	10		360	340	25	7.4
	15		360	350	15	4.3
	20		360	337	9	2.7
	24		360	336	1	.3
	28		360	336	0	0
	32		360	292	0	0
3	[1] 6	25	160	129	21	16.3
	[1] 6	25	160	135	37	27.4
	[1] 6	25	160	137	28	20.4
	10	16	480	400	52	13.0
	15	7	480	409	66	16.1
	20	5	480	400	24	6.0
	24	4	480	350	5	1.4
	28	3	480	320	0	0

[1] Transplanted to bench in first, second, and third leaf stages, respectively.

In the second series the same temperatures were employed, and the seed used was from the same lot of barley grown in 1922. Three hundred and sixty seeds were sown in soil maintained at each of six temperatures. When the plants reached the third-leaf stage they were transplanted to the greenhouse bench, where they were grown until the stripe-diseased plants had developed sufficiently to be counted.

The results shown in Table 2, series 2, indicate that in this case 10° C. was the temperature most conducive to stripe-disease development. The upper limiting temperature seemed to be somewhat above 24°, since at this temperature one stripe-diseased plant developed.

Inasmuch as the highest percentage of infection occurred at the lowest temperature, it was decided to try the effect of a still lower soil temperature. Accordingly, in the third series (Table 2) the temperatures ranged from 6° to 28° C. The plants grown at 6° were equally divided into three lots and were transplanted from the tanks when in the first-leaf, second-leaf, and third-leaf stages, respectively. All the other plants were transferred to the greenhouse bench when the third-leaf stage had been reached, the average temperature of the greenhouse being about 25°. Again the greatest amount of infection occurred at the lowest temperature, although in this series slightly more stripe disease developed at 15° than at 10°. The differences in infection in the three lots grown at 6° and transferred to the warm greenhouse bench at different stages were not statistically significant, showing that the influence of soil temperature on the development of stripe disease does not extend beyond the time of emergence.

To secure additional data on this phase, the two following series of experiments were conducted: In series 1 the two temperatures 28° and 12° C. were used. Naturally inoculated seed of Wisconsin Pedigree No. 6 barley was sown in soil maintained at these temperatures. When the plants emerged, two-thirds of them at each temperature were transferred to the other temperature, that is, approximately two-thirds of those that had grown to emergence at 12° were transferred to the tanks maintained at 28°, while a like number that had grown to emergence at 28° were transferred to a 12° soil-temperature environment. The remainder of the plants were kept at the respective temperatures at which they had been grown to emergence. When in the fourth-leaf stage, the plants were transferred to the greenhouse bench, where they were grown until final data were taken. The data shown in Table 3 indicate that the change in soil temperature after the plants had emerged had no effect upon the percentage of stripe-diseased plants.

TABLE 3.—*Effect on the development of stripe disease of growing barley at a high soil temperature until after the time of emergence and then at a low soil temperature and vice versa*

Series	Soil temperature		Plants grown	Plants infected	
	Before emergence	After emergence			
	° C.	° C.	*Number*	*Number*	*Per cent*
1	28	12	1,280	14	1.1
	28	25	606	1	.16
	12	25	1,322	218	16.5
	12	12	657	110	16.7
2	25	12	634	12	1.89
	25	25	595	6	1.00
	12	25	666	87	13.06
	12	12	647	85	13.14

The fact that in series 1 a slightly greater percentage of stripe disease occurred in the lot transferred from 28° to 12° C. (1.1 per

cent) than occurred in the lot grown continuously at relatively high temperatures (0.15 per cent) may have been due to the fact that some plants emerged after the transfer had been made. The same may be said about the results obtained in series 2 (Table 3), in which 25° was used as the higher temperature. The same procedure used in series 1 was followed in series 2 except that approximately one-half instead of two-thirds of the plants were transferred at the time of emergence. It will be noted that in the lot transferred from 25° to 12°, 12 plants, or 1.89 per cent, were diseased, while in the lot remaining at 25° only 6 plants, or 1 per cent, were infected. Undoubtedly this again was due to plants whose emergence was delayed until after the cans had been transferred. On the other hand, in both series there was nearly the same relative amount of infection in the plants that had been transferred at the time of emergence from 12° to the higher temperatures as occurred in the plants that had been kept at 12° after the time of emergence.

In order to determine to what extent, if any, the soil-moisture content previous to the time of emergence influences the development of stripe disease in plants grown from naturally inoculated seed, experiments were conducted under controlled conditions with soil moisture as the varied factor. In the first experiment, which was of a preliminary nature, 600 seeds of naturally inoculated Wisconsin Pedigree No. 6 barley were sown in the greenhouse bench in soil the moisture content of which had been adjusted to 44 per cent of saturation. A like number of seeds were sown in soil that was heavily watered after sowing and that received a daily watering, so that its moisture content probably remained near 90 per cent of saturation. Both sections of the greenhouse bench were covered with a heavy canvas to lessen evaporation and to maintain a more or less uniform soil temperature, ranging from 13° to 18°, with a mean temperature of about 15° C. These conditions were maintained until the plants emerged. The stripe-disease data taken later and shown in Table 4 seem to indicate that the excessive soil moisture inhibited to some extent the development of stripe disease, as in the wetter soil 16 per cent and in the drier soil 25 per cent of the plants became stripe diseased.

TABLE 4.—*Effect of soil moisture during period of emergence on development of stripe disease in Wisconsin Pedigree No. 6 barley grown in the greenhouse from naturally inoculated seed, Arlington Experiment Farm, Rosslyn, Va.*

Soil		Plants grown	Plants infected	
Temperature	Moisture [1]			
° C.	*Per cent*	*Number*	*Number*	*Per cent*
13–18	90–95	520	83	16
13–18	44	585	148	25

[1] Expressed as percentage of saturation.

A similar experiment was then tried with a number of different seed lots, as shown in Table 5. The drier soil was adjusted to 40 per cent of its water-holding capacity, while, as in the previous experiment, the wetter soil was kept near saturation. One hundred seeds of

each lot were used at each moisture. The temperature of the greenhouse was kept as near 15° C. as possible. The same procedure was followed as before, and similar results were obtained. The experiment was repeated (series 2), and again the results indicated that excessive soil moisture before emergence tends to inhibit stripe-disease development.

TABLE 5.—*Effect of extremes of soil moisture on development of stripe disease in different lots of barley grown from naturally inoculated seed in 3-inch flats in the greenhouse, 100 seeds of each lot being used at each soil moisture, in each series, Arlington Experiment Farm, Rosslyn, Va.*

Lot No.	Seed: Variety	Seed: From crop of—	Seed: Grown in—	Stripe-diseased plants at soil moisture of percentage shown [1]: Series 1, 40 per cent	Series 1, 90 per cent	Series 2, 40 per cent	Series 2, 90 per cent
1	Wisconsin Pedigree No. 6	1922	Wisconsin	7	5.9	(2)	(2)
2	do	1923	do	20	10.7	14.9	9.1
3	do	1924	do	30	14.3	35.5	16.0
4	Unnamed	1924	Illinois	0	0	19.5	3.8
5	do	1925	Minnesota	11	8.3	27.8	15.4
6	Odessa	1925	do	4	5.7	15.7	2.6
	Average			12	7.5	22.7	9.4

[1] Expressed as percentage of saturation. [2] Destroyed by mice.

Experiments were then carried out involving concurrent variations in both soil temperature and soil moisture. The soil temperatures selected were within the range generally found to be conducive to stripe-disease development, namely, 10° to 15° C. The data from four consecutive experiments are shown in Table 6. In series 1, 2, and 3, two temperatures, 10° and 15°, and two soil moistures were used. In series 4 a uniform soil temperature of 12° was employed, and the soil was adjusted to four different degrees of moisture. The seed used in series 1, 2, and 3 was from the same lot of naturally inoculated Wisconsin Pedigree No. 6 barley. A different lot of this seed was used in series 4.

TABLE 6.—*Effect of soil moisture on development of stripe disease in Wisconsin Pedigree No. 6 barley grown from naturally inoculated seed under conditions of controlled soil moisture and soil temperature in the greenhouse, Arlington Experiment Farm, Rosslyn, Va.*

Series	Soil: Temperature	Soil: Moisture [1]	Days to emerge	Plants grown	Plants infected	
	° C.	*Per cent*	*Number*	*Number*	*Number*	*Per cent*
1	10	15	18	56	11	19.6
	15	15	14	52	11	21.2
	10	72	16	44	3	6.8
	15	72	9	52	2	3.8
2	10	35	10	272	33	12.1
	15	35	7	262	31	11.8
	10	62	10	272	24	8.8
	15	62	7	282	24	8.5
3	10	27	12	186	20	10.8
	15	27	10	190	30	15.8
	10	53	12	173	7	4.0
	15	53	10	168	5	3.0
4	12	50	10	270	51	18.9
	12	65	10	390	56	14.4
	12	75	10	380	48	12.6
	12	85	10	200	24	12.0

[1] Expressed as percentage of saturation.

In series 1, one lot of soil was adjusted to 15 and the other to 72 per cent of its water-holding capacity. It will be noted in Table 6 that this difference in soil moisture seemed to cause a considerable difference in the percentage of stripe disease that developed. Similar results were secured in series 2 and 3, in which the same temperatures but two less widely separated degrees of soil moisture were used. In all three series the differences in infection percentages, due apparently to the difference in temperature between 10° and 15° C., were less pronounced than those due to the differences in soil moisture.

In the fourth series a single soil temperature of 12° C. was maintained, but four different soil moistures were employed. It had been planned to use a very low, an extremely high, and two intermediate percentages of soil moisture, but through a miscalculation the lowest and highest adjustments turned out to be 50 and 85 per cent of saturation, respectively. As will be observed in Table 6, the four less extreme differences in soil moisture in series 4 resulted in smaller differences in the development of stripe disease than occurred in the other three series. However, the results from all four series seem to indicate that the development of stripe disease is favored by relatively low soil moistures.

In the next two experiments it was planned to use three temperatures and four soil moistures. This was done in the first series, the results of which are shown in Table 7. In the second series, however, the lowest moisture adjustment proved unsatisfactory and had to be omitted. The data from the remainder of this series also are presented in Table 7. The average percentages of stripe-diseased plants at soil temperatures of 10°, 15°, and 20° C., irrespective of soil moisture differences were: In series 1, 13.7, 11.3, and 7.8, respectively; and in series 2, 22.6, 15.8, and 6.3, respectively. In a general way, these data indicate that the soil with the lowest temperature and with the lowest soil moisture usually was the most favorable for stripe-disease development. There were, however, several marked exceptions to this, both as to temperature and moisture. In series 1, for example, in soil 35 per cent saturated, more stripe disease developed at 20° than at 10°. There is also an unexplainable increase in infection at 10° in the 50 per cent moisture (19.3 per cent) as compared with the 35 per cent moisture (10.5 per cent). A similar but smaller increase occurred at 15°. In series 2 in the soil approximately 95 per cent saturated there seems to be an unduly high percentage of stripe at 10° compared with the infection at 15°. This may have been due to some uncontrolled factor.

In order to compare the above greenhouse results with field data, a date-of-sowing experiment was carried out with seed of Wisconsin Pedigree No. 6 barley. Sowings were made at approximately weekly intervals from September 25 to December 4. Data on soil moisture, soil temperature, and rainfall are recorded in Table 8 together with data on the stripe-disease infection taken the following May.

TABLE 7.—*Combined effects of soil temperature and soil moisture on development of stripe disease in Wisconsin Pedigree No. 6 barley grown in the greenhouse from naturally inoculated seed, Arlington Experiment Farm, Rosslyn, Va.*

Series	Soil		Plants grown	Plants infected		
	Moisture [1]	Temperature				
	Per cent	*° C.*	*Number*	*Number*	*Per cent*	*Average per cent*
1	27	10	216	40	18.5	13.2
		25	205	25	12.2	
		20	194	17	8.8	
	35	10	229	24	10.5	11.9
		15	226	29	12.8	
		20	227	28	12.3	
	50	10	228	44	19.3	14.5
		15	225	37	16.4	
		20	233	18	7.7	
	95	10	186	12	6.5	4.3
		15	183	7	3.8	
		20	163	4	2.5	
2	35	10	213	51	23.9	19.8
		15	243	56	23.0	
		20	241	30	12.4	
	60	10	226	56	24.8	14.8
		15	205	30	14.6	
		20	219	11	5.0	
	95	10	188	36	19.1	10.1
		15	164	16	9.8	
		20	188	3	1.6	

[1] Expressed as percentage of saturation.

TABLE 8.—*Field data on effect of date of sowing and resultant soil temperature and moisture on development of stripe disease in Wisconsin Pedigree No. 6 barley grown from naturally inoculated seed, Arlington Experiment Farm, Rosslyn, Va.*

Plot No.	Date sown	Days to emerge	Soil moisture [1]	Rainfall [2]	Soil temperature [3]		Plants grown	Plants infected	
					Range	Mean [3]			
			Per cent	*Inches*	*° C.*	*° C.*	*Number*	*Number*	*Per cent*
1	Sept. 25	5	71	0	17–26	23	802	10	1.2
2	Oct. 1	7	34	0	13–21	17	1,313	106	8.1
3	Oct. 8	9	8	[4] T	11–22	17	1,662	236	14.2
4	Oct. 15	11	16	1.22	9–21	16	967	140	14.5
5	Oct. 22	12	48	.87	3–20	11	781	115	14.7
6	Oct. 29	15	44	.45	2–20	9	922	167	18.1
7	Nov. 5	17	63	1.00	2–15	9	348	34	9.8
8	Nov. 14	20	55	1.01	2–15	7	521	41	7.9
9	Nov. 22	20	51	2.36	2–15	8	186	8	4.3
10	Dec. 4		66		2–14	3	125	5	4.0

[1] Percentage of saturation at time of sowing.
[2] From sowing to emergence.
[3] Mean of the daily mean temperatures.
[4] T = trace.

The first sowing, made in relatively wet soil (71 per cent saturated) and followed by a rather high average soil temperature (23° C.), resulted in only 1.2 per cent of infection. The second sowing, made in drier soil (34 per cent saturated) and followed by a lower average soil temperature (17°), resulted in 8 per cent of infection. The third sowing, made in very dry soil (only 8 per cent saturated), but followed by the same average soil temperature (17°), showed 14.2 per cent of infection. In the fourth sowing a slight drop in the average soil temperature (16°) was offset by a slight increase in soil moisture (16 per cent of saturation) and the percentage of infection was about the same (14.5). The fifth sowing was made in much wetter soil (48 per cent saturated), but was followed by a considerably lower

average soil temperature (11°). Again these two changes seemed to offset each other as reflected by no appreciable change in the percentage of infection (14.7). The sixth sowing, made in soil not much changed in moisture content (44 per cent saturation), but followed by a 2-degree drop in the average soil temperature (9°), resulted in a crop with 18.1 per cent of stripe disease. The results from subsequent sowings are hardly comparable with the above results, on account of the reduced stands caused by winterkilling. However, in each case the soil was very wet, the rainfall rather heavy, and the soil temperature very low. The plants from the last sowing did not emerge until the following spring. That more infection was not found in the last four plots may possibly be due to the greater readiness with which the infected plants may have succumbed to winterkilling. At any rate, it seems evident that infection can take place at the lowest temperature at which barley will germinate and grow. These results also, on the whole, indicate that both high temperatures (above 20°) and a relatively high moisture content of the soil have an inhibiting effect upon stripe-disease development. Of these two factors, temperature seems to be the more important.

The apparent inhibition of stripe-disease development in plants grown from naturally inoculated seed in nearly saturated soil is possibly due to lack of sufficient oxygen for the rapid growth of the fungus, the oxygen requirements of which may be relatively high, and also, perhaps, to the rapid absorption of water by the seed, which gives the young plant an early start and enables it to grow away from the fungus. On the other hand, the frequently observed increase in the percentage of stripe disease in plants grown to emergence in relatively dry soil may be due to the slow absorption by the seed of sufficient water to bring about rapid germination. This delay in the emergence of the coleoptile from the seed naturally would give the reviving fungus mycelium a better chance to infect it as it grows out between the pericarp and the glume.

From the foregoing remarks it might be expected that soaking naturally inoculated seed previous to sowing it would reduce the amount of stripe disease. Such, however, did not prove to be the case when tried experimentally. Seed of Wisconsin Pedigree No. 5 barley was divided into three lots. The first was sown without treatment of any kind. The second lot was soaked in water and sown immediately. The third lot also was soaked in water, but the seed was dried thoroughly for one hour before being sown. The experiment was further varied by soaking the seed for different lengths of time—1, 2, and 3 hours. No consistent differences were observed in the relative number of diseased plants from the different lots of seed. Soaking the seed in water before sowing evidently does not affect stripe-disease development in the same way as sowing the seed in very wet soil.

CONTROL OF STRIPE DISEASE BY SEED TREATMENT

The writers have reviewed briefly the literature up to 1926 on the control of stripe disease (*18, 19*). Much interesting work has been done since that time, especially with dust fungicides. No attempt will be made to give here a complete review of the rather voluminous literature, but a few references will be cited to show the general trend in seed-treatment practices for the control of stripe disease.

In 1926, Molz (*21*) reported that stripe disease could be successfully combated with Höchst, Tutan, Abavit B, and Agfa. While dust disinfectants are advantageous in that they can be applied considerably in advance of seeding time, he warns against storing treated seed in a damp atmosphere, as injury to the embryo is likely to result, especially after treatment with some of the dust disinfectants now on the market.

In 1927, Lindfors (*20*) stated that stripe disease could be satisfactorily controlled with Abavit B and Tutan Dusts. Uspulun Dust, he stated, was unreliable and Tillantin Dust useless.

Straib (*37*) reported in 1927 excellent stripe-disease control with Höchst and in addition a nearly 10 per cent increase in yield.

Sinning (*33*, *34*) in 1927 and 1929 secured excellent results with Höchst, but Abavit B proved unsatisfactory.

In 1927, Howitt and Stone (*12*) controlled stripe disease in Success hooded barley with Uspulun and Semesan solutions at 45° C. and with Du Pont Dust No. 12. Semesan Dust, Uspulun Dust, Bayer Dust, copper carbonate, and Vitrioline, while relatively ineffective in control, reduced the amount of stripe disease to some extent and increased the yield of grain.

Rodenhiser (*32*), in three years' experiments, secured control with cold and hot (45° C.) solutions of Uspulun, Germisan, and Semesan. However, the results with Germisan were not entirely consistent. He also reported complete control without seed injury with the Du Pont Dusts K–1–A and K–1–B [5] and almost complete control with Du Pont No. 12, S. F. A. No. 225, and Wa Wa Dust. Unlike many other investigators, including the writers, he did not find Höchst extremely effective.

Porter, Yu, and Chen (*27*), in 1929, found liquid treatments more effective than dust treatments on hull-less barley in China.

Reddy and Burnett (*29*), in two years' extensive experiments with numerous varieties of barley, reported in 1930 that they found Ceresan and a number of dust fungicides, made in their laboratory, very effective in stripe-disease control, as well as conducive to increase in yield.

A large number of European workers could be cited, but many of them used dust fungicides relatively unknown or at least unavailable in this country. Most of them report effective control of stripe disease with solutions of Uspulun and Germisan. Some of the fungicidal dusts frequently used with different degrees of success were Agfa, Abavit B, Tutan, Urania, S. F. A. Nos. 225 and 225–V, Höchst, and Tillantin. Conflicting results reported by various workers may be attributed to the use of different varieties of barley, different methods of applying the fungicides, variations in environmental conditions during germination, and a possible variation from year to year in the chemical composition of the compounds used.

The work on the control of stripe disease conducted by the writers from 1922 to 1925 and part of the work of 1926 has been previously reported (*18*, *19*). These experiments were continued up to and during 1930. While certain fungicides were being found ineffective and discarded, others appeared on the market or were submitted by commercial concerns for experimental trial before being offered for

[5] In experiments with Minsturdi barley treated with K–1–A and K–1–B, the writers found in 1927 that these dusts were extremely injurious to the seed. These dusts were the experimental forerunners of Ceresan.

sale. Most of these compounds have now passed the experimental stage and either have been discarded as ineffective or impractical or, having stood the test of experimental investigation, are now being offered on the market as standard commercial fungicides. It seems timely, therefore, to give an account of the results of the seed-treatment experiments carried on from 1926 to 1930, inclusive.

EXPERIMENTS IN 1926

In 1926 seven liquid seed treatments were used in experiments on Wisconsin Pedigree No. 6 spring barley to determine their effect on germination, stripe-disease control, and yield. Uspulun, Semesan, and Bayer Compound were used in 0.5 per cent solutions; Germisan, Corona 620, and Tillantin C were used in 0.25 per cent solutions; and formaldehyde solution was used in the usual 1:320 strength, that is, 1 part of 37 per cent formaldehyde in 320 parts of water, which is a 0.12 per cent solution of formaldehyde gas in water. In each case the seed was placed in loose cheesecloth sacks and immersed for an hour in the different solutions, which were contained in earthenware jars. The seed was then drained and immediately dried, except the lot treated with formaldehyde. This was washed in water before being dried, in order to prevent injury to the seed for it was not possible to sow the seed at once. This washing, it is thought, may have decreased slightly the efficacy of the formaldehyde treatment. The seed was treated at the Arlington Experiment Farm and shipped to Madison, Wis., where it was sown on the West Hill farm of the Wisconsin Agricultural Experiment Station.

To determine the effect of the different seed treatments on germination and stripe-disease control, seed was sown in rod rows at the rate of 250 seeds per row. There were eight replications for each treatment and for each control. Germination counts were made five days after the seedlings had emerged. Stripe-disease data, taken after the plants had headed, are shown in Table 9, along with the germination data. It will be observed that Germisan, as in previous experiments (*18*), was superior to all the other treatments in that it completely eliminated stripe disease. While the other treatments reduced the occurrence of stripe disease to less than 0.5 per cent, the low percentage of stripe disease in the controls renders these results rather insignificant. None of the seed treatments, it seemed, greatly affected germination.

TABLE 9.—*Effect of liquid seed treatments on germination, stripe-disease control, and yield in Wisconsin Pedigree No. 6 barley sown at Madison, Wis., 1926*

Seed treatment				Germination	Stripe-diseased plants		Yield per acre	Increase over control		Odds
No.	Name	Concentration	Time							
		Per cent	*Hours*	*Per cent*	*Number*	*Per cent*	*Bushels*	*Bushels*	*Per cent*	
	Control (untreated)			78.3	112	5.0	43.2			
1	Uspulun	0.5	1	78.0	4	.16	54.9	11.7	27.1	40:1
2	Semesan	.5	1	75.4	2	.07	50.4	7.2	16.7	18:1
	Control (untreated)						43.2			
3	Bayer Compound	.5	1	73.4	4	.15	52.2	9.0	20.8	16:1
4	Germisan	.25	1	72.7	0	0	50.4	2.4	5.0	4:1
	Control (untreated)			71.6	115	5.00	48.0			
5	Corona 620	.25	1	68.2	1	.04	49.6	1.6	3.3	3:1
6	Tillantin C	.25	1	72.8	2	.08	51.8	4.8	10.2	46:1
	Control (untreated)						47.0			
7	Formaldehyde	.12	1	67.2	8	.33	49.6	2.6	5.5	4:1

To secure data on the effect of these seed treatments on yield, a parallel series of sowings was made in 1/80-acre plots. Sufficient seed had been treated for 12 replications, but an unforeseen shortage of land made it necessary to limit the experiment to four replications for each treatment and for each control, thus, unfortunately, making the yield data less significant. Each plot was harvested and threshed separately and the grain carefully weighed. The summarized results, expressed in bushels per acre, are shown in Table 9.

Uspulun, Semesan, Bayer Compound, and Tillantin C increased the yields in all four replications as compared with the yields from the corresponding control plots. Germisan, Corona 620, and formaldehyde showed increased yields in only two out of the four replications. However, only in the case of Uspulun and Tillantin C were these increases even slightly significant. The average yield from all the plots sown to treated seed exceeded the average yield from the control plots by 13 per cent. With only 5 per cent of stripe disease in the control plots at heading time, it seems reasonable to suppose that part of this difference in yield was brought about by the control of other diseases in addition to the control of stripe disease to a greater extent than is indicated by the count of stripe-diseased plants at heading time.

Experiments with dust fungicides for the control of stripe disease also were carried out during the 1926 season, but as the results of these investigations have already been published (*19*), they are not included here.

EXPERIMENTS IN 1927

In the fall of 1926 a number of dust fungicides were used in experiments for the control of covered smut in Tennessee Winter barley. Treated and untreated seed was sown in three parallel series of plots in which the soil had been limed, left untreated, or acidified with ammonium sulphate. The procedure in these experiments has been described in a previous publication (*17*) and need not be repeated here. The amount of stripe disease that appeared in the plots the following spring is shown in Table 10, with the data on the control of this disease.

The relative alkalinity or acidity of the soil seemed to have no marked effect either on the development of stripe disease or on its control by any of the fungicides used. When an average of only 3.8 per cent of stripe disease occurred in the controls, Abavit B, Semesan Jr., and Wa Wa Dust completely prevented its occurrence; with one exception, all the other dusts reduced its occurrence to less than 0.2 per cent.

Seed of Tennessee Winter barley treated with a number of experimental dust disinfectants also was sown in paired rod rows in October, 1926, and the data taken the following May are shown in Table 11. With an average of 3.8 per cent of stripe disease in the controls, only two of the dust fungicides used prevented stripe disease without injuring the seed. The liquid fungicides gave satisfactory control, as usual.

147133—33——3

TABLE 10.—*Stripe-diseased plants in Tennessee Winter barley grown from seed, untreated or treated with different dust disinfectants, and sown in rod rows replicated sixteen times for each disinfectant on each of three plots, one limed, one untreated, and one acidified, Arlington Experiment Farm, Rosslyn, Va., October 16, 1926*

[Data taken in May, 1927]

Seed treatment		Stripe-diseased plants on—			Total infected plants	
No.	Name	Limed soil	Untreated soil	Acidified soil		
		Number	*Number*	*Number*	*Number*	*Per cent*
	Control (untreated)	123	120	98	341	3.5
1	Abavit B	0	0	0	0	0
2	S. F. A. No. 225	1	5	4	10	.10
3	S. F. A. No. 225-V	1	0	0	1	.01
4	S. I. 220	20	11	21	52	.54
5	Semesan	1	1	3	5	.05
6	Semesan Jr.	0	0	0	0	0
	Control (untreated)	124	121	154	399	4.16
7	Du Pont No. 12	0	0	2	2	.02
8	Du Pont No. 45	0	1	1	2	.02
9	Bayer Dust	6	3	3	12	.13
10	Bayer Dust II	1	4	6	11	.11
11	Wa Wa Dust	0	0	0	0	0
12	Mercury C	1	1	1	3	.03
	Total from untreated seed	247	241	252	740	
	Total from treated seed [1]	11	15	20	46	
	Ratio, untreated to treated [1]	22:1	16:1	13:1	16:1	

[1] No. 4 not included.

TABLE 11.—*Control of stripe disease in Tennessee Winter barley by a number of experimental dust fungicides, and also by four liquid fungicides, Arlington Experiment Farm, Rosslyn, Va., 1926–27*

Seed treatment		Stripe-diseased plants	
No.	Name		
		Number	*Per cent*
	Control (untreated)	72	4.0
1	Cuprobol	66	3.7
2	Vitrioline	5	.28
3	Karasch A	7	.4
4	Resorcin	41	2.3
5	Resorcin one-half, copper carbonate one-half	45	2.6
6	Resorcin one-third, copper carbonate two-thirds	54	3.0
	Control (untreated)	76	4.2
7	Resorcin one-third, dextrin two-thirds	40	2.3
8	Mercurous chloride one-half, copper carbonate one-half	20	1.2
9	Mercuric chloride one-half, copper carbonate one-half	0	[1] 0
10	Du Pont No. 50	1	[1] .06
11	Du Pont No. 67	45	2.7
12	Du Pont No. 68	25	1.4
	Control (untreated)	73	4.0
13	Du Pont No. 35	0	0
14	Du Pont No. 42	0	0
15	Du Pont No. 53	3	[1] .15
16	Du Pont No. 57	5	.30
17	Du Pont No. 64	0	0
18	Mercuric oxide one-half, copper carbonate one-half	5	.30
	Control (untreated)	63	3.30
19	Mercuric sulphate one-half, copper carbonate one-half	12	.70
20	Uspulun (0.5 per cent, 1 hour)	1	.06
21	Semesan (0.5 per cent, 1 hour)	0	0
22	Germisan (0.25 per cent, 1 hour)	0	0
23	Formaldehyde (0.12 per cent, 1 hour)	0	0
	Control (untreated)	54	3.0

[1] Seed injury and reduced stand.

In the spring of 1927, further field experiments on the relation of soil reaction and soil moisture to the occurrence and control of stripe disease were carried out on the Arlington Experiment Farm in a manner similar to that previously described for covered smut in barley (*17*). Three plots, each 18 by 132 feet, were treated as follows: Plot 1 was given a dressing of air-slaked lime at the rate of 4,000 pounds per acre, plot 2 was left untreated, and to plot 3 ammonium sulphate was added at the rate of 400 pounds per acre. The lime was applied the day before sowing and thoroughly disked into the soil. The ammonium sulphate was applied shortly before the land was leveled preparatory to sowing. Composite soil samples, taken immediately before sowing, showed the following reactions: Plot 1, pH 8.4; plot 2, pH 6; plot 3, pH 5.2.[6] The soil contained 50 per cent of its water-holding capacity at the time of sowing the seed on March 17. Rain was excluded from half of each plot until April 2, when the seedlings emerged. During this time the other half of each plot was artificially watered with the equivalent of a soil-saturating rain. In addition to this artificial watering, the rainfall during this period was 0.75 inch.

The infection data taken later in the season are shown in Table 12. No significant differences in stripe-disease development or control in the three plots were evident. Therefore, it follows that in the type of soil used, Keyport silt loam, stripe-disease development, or its control by the fungicides used was not affected by a difference in soil reaction over the range from pH 5.2 to pH 8.4 or by a range in soil moisture from 50 per cent saturation to the degree of saturation obtained by the method described. These results do not parallel very closely those shown in series 4, Table 6.

TABLE 12.—*Stripe-diseased plants in Wisconsin Pedigree No. 6 barley grown from naturally inoculated seed, untreated or dusted with different seed disinfectants, and sown in rod rows replicated sixteen times for each disinfectant on each of three plots, one limed, one untreated, and one acidified, half of each plot being kept dry until after emergence and the other half heavily watered, Arlington Experiment Farm, Rosslyn, Va., 1927*

Seed treatment		Stripe-diseased plants in—									
		Wet soil					Dry soil				
No.	Name	Limed	Untreated	Acidified	Total	Per cent	Limed	Untreated	Acidified	Total	Per cent
	Control (untreated)	230	241	205	676	12.2	268	229	209	706	12.8
1	Abavit B	6	4	4	14	.2	2	3	4	9	.1
2	Tutan	8	5	2	15	.2	16	8	2	26	.3
3	S. F. A. No. 225–V	0	1	0	1	[a] T	0	0	0	0	0
4	Semesan	0	0	1	1	T	0	1	0	1	T
5	Du Pont No. 12	0	0	0	0	0	0	0	0	0	0
6	Bayer Dust	1	2	1	4	T	6	3	4	13	.2
7	Wa Wa Dust	0	0	0	0	0	0	0	0	0	0
	Infected plants from treated seed	15	12	8	35	------	24	15	10	49	------
	Ratio, untreated to treated	15:1	20:1	25:1	19:1	------	11:1	15:1	21:1	14:1	------

[a] T=trace.

[6] These determinations were made by E. F. Snyder, associate chemist, Bureau of Chemistry and Soils whose assistance is gratefully acknowledged.

With an average of 12.5 per cent of stripe disease in the controls, Wa Wa Dust and Du Pont No. 12 eliminated the disease completely, while the rest of the treatments reduced its occurrence to less than 0.5 per cent.

In addition to the seven fungicidal dusts used in the above experiment, in 1927 six other dusts and one liquid fungicide were employed in additional seed-treatment experiments for the control of stripe disease in spring barley.

Five of the thirteen dust fungicides used came from Germany and are not commercially available in this country, namely: Abavit B, Tutan, S. I. No. 220, S. F. A. No. 225–V, and Höchst. Höchst also is known as Trockenbeize Tillantin. The following four dusts were supplied by the E. I. du Pont de Nemours & Co.: Semesan, Semesan Jr., and Du Pont Dust Nos. 12 and 45. The Bayer Co. furnished Bayer Dust and Bayer Dust II. Wa Wa Dust came from the Chicago Process Co., and Mercury C from the Roessler & Hasslacher Chemical Co. The liquid fungicide used was Germisan, made by Saccharin-Fabrik Aktiengesellschaft, Magdeburg, Germany, and not commercially available in this country. In previous experiments this fungicide had controlled stripe disease almost perfectly.

The following eight lots of barley were used: Minsturdi barley, crop of 1925, received from J. J. Christensen, St. Paul, Minn.; unnamed variety, crop of 1925, received from L. W. Melander, St. Paul, Minn.; five lots of Wisconsin Pedigree No. 6 barley, crops of 1922, 1923, 1924, 1925, and 1926, received from J. G. Dickson, Madison, Wis.; and Manchuria barley, crop of 1926, received from A. N. Hume, Brookings, S. Dak.

The dust fungicides were applied to the seed at the rate of 4 ounces per bushel, after which the seed was continuously shaken for about 30 minutes in a closed container, as described and illustrated in a previous paper (*17*). The seed was then shaken in a fine sieve so that all the excess dust was removed. By means of this "excess method" every seed was coated as thoroughly as it would be in the most efficient dusting machine.

The Germisan was applied by immersing the seed in a 0.25 per cent solution at room temperature for one hour, after which it was allowed to dry.

The seed was sown at the rate of 250 seeds per row in rod rows replicated four times for each treatment and each seed lot in each of two parallel series: Series 1 was sown on the Arlington Experiment Farm on March 10, series 2 was sown on the East Hill farm of the Wisconsin Agricultural Experiment Station on April 27. A third series was sown at Madison, Wis., on May 1, at the rate of 10 grams of seed per rod row, using only five of the seed lots and devoting only two rod rows to each treatment of each seed lot.

Emergence data on series 1, taken April 1 to 6, 1927, are presented in Table 13. Owing to unfavorable soil conditions in part of the field, two of the seed lots emerged so irregularly that emergence data on these are not included. It will be observed that Tutan and Wa Wa Dust caused marked reductions in the percentages of germination, while none of the other treatments seemed to have any appreciable effect.

Stripe-disease data on series 1 were taken on May 28. The number of stripe-diseased plants from each lot of seed is given in Table 14, together with the average percentages of infection in the whole series.

Stripe disease was eliminated by Tutan, S. F. A. No. 225–V, Wa Wa Dust, Höchst, and by the water solution of Germisan. With the exception of S. I. No. 220, which was relatively ineffective, all the other dusts reduced the occurrence of stripe disease to a mere trace, while an average of 10.8 per cent appeared in the controls. This general average was lowered by the relatively light infection in the Manchuria barley and in the Wisconsin Pedigree No. 6 barley grown from 1926 seed.

TABLE 13.—*Emergence data on barley grown from six lots of seed, untreated or treated with different fungicides, and sown at the rate of 250 seeds per rod row replicated four times for each treatment and each seed lot, Arlington Experiment Farm, Rosslyn, Va., March 10, 1927*

[Data taken March 29 to April 6]

Seed treatment		Percentage of emergence from 1,000 seeds of—						Average emergence	Increase or decrease in emergence as compared with average of controls
				Wisconsin Pedigree No. 6, crop of—					
No.	Name	Minsturdi, crop of 1925	Unnamed variety, crop of 1925	1924	1925	1926	Manchuria, crop of 1926		
								Per cent	*Per cent*
	Control (untreated)	84.0	65.5	84.3	85.4	90.3	88.1	82.9	
1	Abavit B	79.3	59.1	90.3	85.2	88.2	86.0	81.4	−1.8
2	Tutan	63.9	56.3	73.2	81.3	68.2	71.6	69.1	−14.1
3	S. F. A. No. 225–V	84.5	62.0	88.2	87.7	89.8	83.5	82.6	−.6
4	S. I. No. 220	76.7	67.5	86.9	87.2	89.9	84.4	82.1	−1.1
5	Semesan	86.0	64.1	92.0	87.8	90.8	92.4	85.5	+2.3
6	Semesan Jr	84.2	67.1	90.5	84.9	93.4	89.8	85.0	+1.8
7	Du Pont No. 12	70.0	63.6	86.4	81.6	86.6	84.9	78.9	−4.3
	Control	84.0	62.9	88.0	86.2	90.1	89.8	83.5	
8	Du Pont No. 45	57.1	51.4	82.7	83.2	85.2	81.4	73.5	−9.7
9	Bayer Dust	80.7	67.9	88.8	85.9	90.4	90.1	84.0	+.8
10	Bayer Dust II	82.3	65.1	90.4	85.6	89.9	88.9	83.7	+.5
11	Wa Wa Dust	45.9	32.0	74.3	80.5	64.5	58.7	59.3	−23.9
12	Mercury C	86.0	67.8	91.6	86.3	90.5	89.0	85.2	+2.0
13	Höchst	78.3	61.3	86.8	85.1	83.3	82.8	79.6	−3.6
14	Germisan (0.25 per cent, 1 hour)	86.0	71.7	86.9	85.9	91.7		84.4	+1.2

Series 2 was sown at Madison, Wis., April 27, and the seedlings emerged May 9. Emergence data taken eight days later are shown in Table 15. In contrast with similar data secured in series 1 (Table 13), none of the treatments showed any appreciable effect upon the percentages of germination, with the possible exception of Wa Wa Dust, which, as compared with the controls, reduced the average percentage of germination 7 per cent.

Stripe-disease data were taken in July. The number of stripe-diseased plants from each lot of treated and untreated seed are shown in Table 16, together with the average percentages of stripe disease for each treatment. When an average of only 8.4 per cent of infection occurred in the controls, the treatments were not so effective as were those in series 1, when stripe disease in the controls averaged 10.8 per cent. The soil-moisture content between the dates of sowing and emergence in series 2 varied from 30 to 60 per cent of saturation, while in series 1 it was consistently over 50 per cent during the corresponding period. Undoubtedly the relatively lower moisture content of the soil in series 2, especially during the first few days after sowing, was responsible for the slightly decreased efficiency of the dust fungicides in this series.

TABLE 14.—*Stripe-diseased barley plants grown from different varieties or lots of seed, untreated or treated with different seed disinfectants, and sown in rod rows replicated four times for each treatment and seed lot, Arlington Experiment Farm, Rosslyn, Va., 1927*

Seed treatment		Stripe-diseased plants from 1,000 seeds of—								Total plants infected	
		Minsturdi, crop of 1925	Unnamed variety, crop of 1925	Wisconsin Pedigree No. 6, crop of—					Manchuria, crop of 1926		
No.	Name			1922	1923	1924	1925	1926			
										Number	*Per cent*
	Control (untreated)	105	86	58	107	122	92	13	4	587	10.83
1	Abavit B	0	1	0	1	1	0	0	0	3	.06
2	Tutan	0	0	0	0	0	0	0	0	0	0
3	S. F. A. No. 225–V	0	0	0	0	0	0	0	0	0	0
4	S. I. No. 220	22	22	40	25	74	43	5	7	238	4.42
5	Semesan	0	0	0	0	3	0	0	1	4	.07
6	Semesan Jr	0	1	2	0	1	2	3	0	9	.16
7	Du Pont No. 12	0	0	0	0	1	0	0	0	1	.02
	Control (untreated)	95	102	88	75	92	82	11	7	552	10.80
8	Du Pont No. 45	1	4	0	0	2	1	0	0	8	.17
9	Bayer Dust	3	3	0	0	3	0	0	0	9	.16
10	Bayer Dust II	2	2	2	1	15	0	0	0	22	.40
11	Wa Wa Dust	0	0	0	0	0	0	0	0	0	0
12	Mercury C	2	0	0	0	3	0	0	0	5	.09
13	Höchst	0	0	0	0	0	0	0	0	0	0
14	Germisan (0.25 per cent, 1 hour)	0	0	0	0	0	0	0	0	0	0
	Total in controls	200	188	146	182	214	174	24	11	1,139	-------
	Total from treated seed [1]	8	11	4	2	29	3	3	1	61	-------
	Ratio, untreated to treated [1]	25:1	17:1	37:1	91:1	7:1	58:1	8:1	11:1	19:1	-------

[1] No. 4 not included.

TABLE 15.—*Emergence data on barley grown from eight lots of seed, untreated or treated with different seed disinfectants, and sown at the rate of 250 seeds per rod row replicated four times for each treatment and seed lot, at Madison, Wis., April 27, 1927*

Seed treatment		Percentage of emergence from 1,000 seeds of—								Average emergence	Increase or decrease in emergence as compared with average of controls
				Wisconsin Pedigree No. 6, crop of—							
No.	Name	Minsturdi, crop of 1925	Unnamed variety, crop of 1925	1922	1923	1924	1925	1926	Manchuria, crop of 1926		
										P. ct.	*P. ct.*
	Control (untreated)	74	71	68	68	63	74	72	77	71	-------
1	Abavit B	67	63	67	71	66	72	68	72	68	−2
2	Tutan	68	65	66	72	65	79	65	75	69	−1
3	S. F. A. No. 225–V	72	66	73	69	69	74	73	74	71	+1
4	S. I. No. 220	62	69	73	67	69	79	67	75	70	0
5	Semesan	66	72	74	74	76	76	75	75	74	+4
6	Semesan Jr	71	69	70	73	70	73	74	79	72	+2
7	Du Pont No. 12	63	63	65	63	70	71	71	73	67	−3
	Control (untreated)	68	65	69	60	64	77	72	72	68	-------
8	Du Pont No. 45	70	65	65	64	66	76	71	70	68	−2
9	Bayer Dust	73	73	71	68	70	76	74	72	72	+2
10	Bayer Dust II	74	72	72	67	69	76	75	74	72	+2
11	Wa Wa Dust	55	52	68	59	62	76	67	61	63	−7
12	Mercury C	77	72	77	72	75	74	73	71	74	+4
13	Höchst	72	67	------	------	73	73	71	-------	71	+1
14	Germisan (0.25 per cent, 1 hour)	75	68	------	------	73	76	74	-------	73	+3

TABLE 16.—*Stripe-diseased barley plants grown from different varieties or lots of seed, untreated or treated with different seed disinfectants, and sown in rod rows replicated four times for each treatment and seed lot, Madison, Wis., 1927*

Seed treatment		Stripe-diseased plants from 1,000 seeds of—								Total stripe-diseased plants	
		Minsturdi, crop of 1925	Unnamed variety, crop of 1925	Wisconsin Pedigree No. 6, crop of—					Manchuria, crop of 1926		
No.	Name			1922	1923	1924	1925	1926			
										Number	*Per cent*
	Control (untreated)	96	74	36	41	102	47	11	10	417	8.60
1	Abavit B	0	0	0	0	1	0	1	0	2	.04
2	Tutan	1	7	7	1	4	4	1	0	25	.50
3	S. F. A. No. 225–V	0	6	0	0	1	0	0	0	7	.14
4	S. I. No. 220	15	9	53	20	77	33	6	3	216	4.15
5	Semesan	3	2	1	1	3	2	0	0	12	.23
6	Semesan Jr	2	2	3	0	7	0	0	0	14	.27
7	Du Pont No. 12	0	0	0	0	1	0	0	0	1	.02
	Control (untreated)	105	62	40	38	96	56	7	5	409	8.10
8	Du Pont No. 45	0	1	1	1	9	0	0	0	12	.23
9	Bayer Dust	1	4	2	0	9	0	2	0	18	.35
10	Bayer Dust II	3	3	5	1	11	0	0	1	24	.45
11	Wa Wa Dust	0	0	0	0	0	0	0	0	0	0
12	Mercury C	2	1	0	1	5	1	0	0	10	.20
13	Höchst	0	0	0	0	0	0	0	0	0	0
14	Germisan (0.25 per cent, 1 hour)	0	1	0	0	0	0	0	0	1	.02
	Total in controls	201	136	76	79	198	103	18	15	826	-------
	Total from treated seed [1]	12	27	19	5	51	7	4	1	126	-------
	Ratio, untreated to treated [1]	17:1	5:1	4:1	16:1	4:1	15:1	5:1	15:1	7:1	-------

[1] No. 4 not included.

Wa Wa Dust and Höchst were the only fungicides that prevented the disease completely, although Abavit B, Du Pont No. 12, and Germisan gave very nearly perfect control. All the remaining dusts reduced the amount of infection to 0.5 per cent or less, with the exception of S. I. No. 220, which, as in series 1, was relatively ineffective.

TABLE 17.—*Occurrence of stripe disease in spring barley grown from five lots of seed, untreated or treated with different fungicides, and sown in paired rod rows at the rate of 10 grams per row, Madison, Wis., May 1, 1927*

Seed treatment		Infected plants from seed of—					Total plants infected	
		Minsturdi, crop of 1925	Unnamed variety, crop of 1925	Wisconsin Pedigree No. 6, crop of—				
No.	Name			1924	1925	1926		
							Number	*Per cent*
	Control (untreated)	81	45	77	32	8	243	10.56
1	Abavit B	0	0	2	0	0	2	.09
2	Tutan	4	0	0	1	0	5	.22
3	S. F. A. No. 225–V	1	0	1	0	0	2	.10
4	S. I. No. 220	16	15	55	21	6	113	4.87
5	Semesan	0	1	3	0	1	5	.20
6	Semesan Jr	1	2	8	0	0	11	.48
7	Du Pont No. 12	0	0	1	0	0	1	.04
	Control (untreated)	70	38	100	24	10	242	10.52
8	Du Pont No. 45	1	0	9	1	0	11	.47
9	Bayer Dust	2	0	6	2	0	10	.41
10	Bayer Dust II	1	1	5	0	0	7	.30
11	Wa Wa Dust	0	0	0	0	0	0	0
12	Mercury C	1	0	2	0	0	3	.13
13	Höchst	0	0	0	0	0	0	0
14	Germisan (0.25 per cent, 1 hour)	0	0	0	0	0	0	0

In the series sown May 1, the results were very similar to those described above. (Table 17.) Wa Wa Dust, Höchst, and Germisan solution gave complete control, while all the other fungicides reduced the percentage of infection to less than 0.5 per cent, with the exception of S. I. No. 220, which was relatively ineffective, as before.

In Tables 14 and 16 it will be observed that in Wisconsin Pedigree No. 6 barley the 1923 seed lot in each case produced the highest ratio between the total number of diseased plants from untreated and treated seed. This seems to indicate that, under the same conditions, the treatments, as a whole, were relatively more effective in stripe-disease control in this seed lot than in the seed from the 1924 crop, which in each case shows the lowest ratio between numbers of diseased plants from untreated and treated seed. In this respect the 1925 seed lot occupies a position next to that of the 1923 seed lot in both series, while the relative positions of the 1922 and 1926 seed lots with respect to one another are reversed in the two series.

These data, although not highly significant, suggest the possibility that naturally inoculated seed of a given variety of barley from one crop year may respond to seed treatment more readily than seed of this same variety grown in another crop year. This difference in response to seed treatment may be dependent on certain environmental conditions which obtain during the period in which stripe-disease inoculation takes place and which may cause the infective material to be more deep-seated in the seed in some years than it is in others. On the other hand, it seems evident from these data that the age of the seed does not materially affect the seed-borne stripe-disease organism so far as its susceptibility to control by seed treatment is concerned. If this were the case, it would be reasonable to expect that the seed treatments would have been most effective in the control of stripe disease in the 1922 seed lot and least effective in the 1926 seed lot. However, such was not the case.

In order to determine what effect, if any, the fungicides had on the stand in series 2, it was planned to make a total plant count. This, however, proved to be impracticable on account of the hard, dry soil. Therefore, total culm counts were made, and the results are shown in Table 18. It will be observed that, on the whole, the treatments caused little increase or decrease in the average number of culms per thousand seeds sown, as compared with the number of culms from an equal number of untreated seeds. Only in the case of Semesan was the increase barely significant, according to the odds computed by Student's method. Likewise, Wa Wa Dust was the only treatment that appeared to cause a significant decrease in the relative numbers of culms. As a whole, the treatments seemed to cause an average increase of only 0.72 per cent in the total number of culms, as compared with the controls. However, since over 8 per cent of the culms in the control rows were stripe diseased and an average of not over 0.5 per cent of infection occurred in any of the rows from treated seed, some benefits from seed treatment are apparent.

TABLE 18.—*Number of culms of barley grown from eight lots of seed, untreated or treated with different seed disinfectants, and sown at the rate of 250 seeds per row in paired rod rows replicated twice for each treatment and seed lot, Madison, Wis., 1927*

Seed treatment		Total culms from 1,000 seeds of—								Summary			
No.	Name	Minsturdi, crop of 1925	Unnamed variety, crop of 1925	Wisconsin Pedigree No. 6, crop of—					Manchuria, crop of 1926	Average number culms from 1,000 seeds	Increase or decrease, as compared with control		
				1922	1923	1924	1925	1926			*Culms*	*Per cent*	*Odds*
	Control (untreated)	1,012	1,195	1,208	1,022	983	1,053	1,042	1,217	1,092			
1	Abavit B	932	1,066	1,220	1,028	1,080	1,056	974	1,179	1,067	−30	−2.7	8:1
2	Tutan	974	1,191	1,228	1,199	1,125	1,073	953	1,187	1,116	+19	1.7	3:1
3	S. F. A. No. 225–V	972	1,170	1,351	1,328	1,242	1,110	1,024	1,171	1,171	+74	6.7	12:1
4	Semesan	1,016	1,203	1,268	1,295	1,258	1,113	1,094	1,216	1,183	+86	7.8	48:1
5	Semesan Jr.	1,052	1,147	1,223	1,155	1,208	1,044	1,072	1,200	1,138	+41	3.7	14:1
6	Du Pont No. 12	1,034	1,064	1,092	995	1,148	1,054	1,070	1,165	1,078	−19	−1.7	4:1
7	S. I. No. 220												
	Control (untreated)	1,079	1,160	1,089	1,075	1,118	1,123	1,025	1,143	1,102			
8	Du Pont No. 45	970	1,124	1,106	1,058	1,139	1,082	932	1,137	1,069	−28	−2.6	8:1
9	Bayer Dust	1,048	1,129	1,095	1,144	1,213	1,070	1,027	1,158	1,111	+14	1.3	2:1
10	Bayer Dust II	1,061	1,157	1,086	1,123	1,212	1,054	1,056	1,157	1,113	+16	1.5	3:1
11	Wa Wa Dust	810	962	996	1,095	1,124	1,036	912	997	992	−105	−9.6	51:1
12	Mercury C	1,046	1,236	1,090	1,266	1,238	1,127	970	1,210	1,148	+51	4.6	9:1
13	Höchst	966	1,036			1,342	1,082	932		1,072	−25	−2.3	1:1
14	Germisan (0.25 per cent, 1 hour)	1,080	996			1,305	1,145	1,008		1,107	+10	.9	2:1

EXPERIMENTS IN 1928

During the spring of 1928, data again were taken on the occurrence of stripe disease in Tennessee Winter barley grown from seed that had been treated with different fungicides and sown the preceding fall on the Arlington Experiment Farm. The seed had been sown in rod rows replicated twenty times for each treatment in each of two parallel series. Series 1 had been sown September 21, 1927, in soil the moisture content of which amounted to only 13 per cent of saturation and which received no rainfall until after the plants had emerged. Series 2 had been sown October 7, 1927, in soil the moisture content of which was 65 per cent of saturation and which received an inch of rainfall three days after the seed had been sown. The mean soil temperatures during the periods of emergence in series 1 and 2 were 18° and 16° C., respectively. Tests in the field and in the greenhouse failed to show that any of the treatments had any appreciable effect on the percentages of germination, as shown in Table 19.

The stripe-disease data, taken in May, 1928, also are shown in Table 19. The infection in the controls in series 2 was much more severe than in series 1, probably because of the lower soil temperatures that prevailed after series 2 was sown. However, in spite of the more favorable conditions for stripe-disease development in series 2, stripe-disease control by all the dusts was better in this series than in the dry soil of series 1. The outstanding fungicide in both series was Höchst. Abavit B, Mercury C, Wa Wa Dust, and several others were fairly effective. However, a number of these contain a mercury content too high to make them practicable as seed-treatment compounds for barley, in view of the fact that cheaper and equally effective fungicides are now on the market.

TABLE 19.—*Emergence of, and stripe-disease control in, Tennessee Winter barley grown from treated and untreated seed sown on Arlington Experiment Farm, Rosslyn, Va., in rod rows replicated 20 times for each treatment and control in each of two series: Series 1 sown September 21, 1927, in soil 13 per cent saturated; series 2 sown October 7, 1927, in soil 65 per cent saturated*

Seed treatment		Emergence		Stripe-diseased plants			
No.	Name	Field	Greenhouse	Series 1		Series 2	
		Per cent	*Per cent*	*Number*	*Per cent*	*Number*	*Per cent*
	Control (untreated)	75	76	199	5.75	403	13.71
1	Abavit B	75	86	15	.43	0	0
2	S. F. A. No. 225	80	83	27	.77	5	.15
3	S. F. A. No. 225-V	74	92	29	.82	6	.18
4	Höchst	76	91	2	.05	0	0
5	Tutan	80	92	110	2.93	90	2.76
6	Vitrioline	79	86	198	5.37	196	6.34
7	Mercury C	78	85	25	.68	2	.06
	Control (untreated)	81	80	210	5.74	428	14.46
8	Wa Wa Dust	79	86	10	.27	4	.13
9	Semesan	80	87	17	.45	5	.16
10	Semesan Jr.	80	87	13	.34	5	.16
11	Du Pont No. 35	81	87	26	.71	6	.18
12	Du Pont No. 45	78	89	23	.62	2	.06
13	Du Pont No. 53	82	88	62	1.67	36	1.13
14	Du Pont No. 64	80	88	27	.75	2	.06

In the spring of 1928 further experiments on the control of stripe disease in spring barley were conducted with fungicides that had proved effective in previous tests, as well as with a few additional experimental dust fungicides recently submitted by commercial concerns. Most of the latter were used in a preliminary experiment along with other dusts of questionable merit, but three were used in the more frequently replicated trials.

The seed used was Wisconsin Pedigree No. 6 barley from the 1925 and 1926 crops grown on the Rock County farm, near Janesville, Wis. The dusts were applied at the rate of 3 ounces per bushel and thoroughly mixed with the seed in a mechanical contrivance, as previously described (*17*). Two parallel series were sown, as before, the first at Arlington Experiment Farm and the second at Madison, Wis. Because of unfavorable weather and soil conditions, the plants in the first series failed to develop beyond the seedling stage, and no data of value were obtained from them.

At Madison, Wis., the seed was sown April 26 on the East Hill farm of the Wisconsin Agricultural Experiment Station. In the first experiment, in which dusts of unknown or questionable merit were tested, only seed from the 1926 crop was used, and 4 rod rows were devoted to each treatment. In the second experiment 24 rod rows were used for each treatment on each seed lot. Germination tests were made in the greenhouse.

The infection data taken on the first experiment at Madison, Wis., are shown in Table 20. Only two of the experimental dusts used showed any especial effectiveness in stripe-disease control; namely, Bayer 189 and Abavit Special. Different dilutions of formaldehyde, paraformaldehyde, or iodine with talc or kaolin proved ineffective, notwithstanding certain claims that had been made to the contrary.

TABLE 20.—*Stripe-diseased plants in Wisconsin Pedigree No. 6 barley grown from seed, untreated or treated with various experimental dust disinfectants, and sown in rod rows replicated four times for each treatment, Madison, Wis., April 26, 1928*

Seed treatment		Stripe-diseased plants		Seed treatment		Stripe-diseased plants	
No.	Name			No.	Name		
		Number	*Per cent*			*Number*	*Per cent*
	Control (untreated)	83	10.4	16	Iodine, 3 per cent	70	8.8
1	Bayer HT-3	69	8.6	17	Iodine, 2 per cent	72	9.0
2	Agfa 331	8	1.0	18	Metaphen	32	4.0
3	Bayer No. 192	20	2.5	19	Du Pont No. 68	37	4.6
4	Bayer No. 194	50	6.3	20	Abavit Special	1	.1
5	Bayer No. 196	16	2.0	21	Sulphur + potassium permanganate	82	10.3
6	Bayer No. 200	55	6.9		Control (untreated)	80	10.0
7	Bayer No. 189	1	.1	22	Formaldehyde, dry, 6 per cent on talc	75	9.4
	Control (untreated)	77	9.6	23	Formaldehyde, dry, 5 per cent on talc	73	9.1
8	U. T. 348	21	2.6	24	Formaldehyde, dry, 4 per cent on talc	66	8.3
9	U. T. 488	45	5.6	25	Bayer Dust	13	1.6
10	Paraformaldehyde, 20 per cent	30	3.8	26	Copper oxychloride	57	7.1
11	Paraformaldehyde, 15 per cent	49	6.1	27	Vitrioline	28	3.5
12	Paraformaldehyde, 10 per cent	67	8.4	28	Tutan	8	1.0
13	Paraformaldehyde, 5 per cent	76	9.5				
14	Iodine, 5 per cent	53	6.6				
	Control (untreated)	73	9.1				
15	Iodine, 4 per cent	69	8.6				

Infection data on the second experiment are presented in Table 21, together with the germination data secured in the greenhouse. None of the treatments, it will be observed, seemed to have any pronounced effect on germination.

TABLE 21.—*Emergence of, and stripe-diseased plants in, Wisconsin Pedigree No. 6 barley grown from 1925 and 1926 seed, untreated or treated with different seed disinfectants, and sown in paired rod rows replicated twelve times for each seed lot and each treatment at Madison, Wis., April 26, 1928*

Seed-treatment		Emergence	Total stripe-diseased plants from—			
No.	Name		1925 seed		1926 seed	
		Per cent	*Number*	*Per cent*	*Number*	*Per cent*
	Control (untreated)	88	259	5.40	705	13.40
1	Abavit B	90	6	.13	46	.87
2	S. F. A. No. 225–V	89	13	.27	67	1.27
3	Höchst	89	0	0	0	0
4	Semesan	89	21	.44	71	1.34
5	Semesan Jr	80	30	.63	72	1.36
6	Du Pont K–1–C	92	0	0	0	0
	Control (untreated)	95	240	5.00	653	12.37
7	Du Pont K–1–D	90	1	.02	0	0
8	Wa Wa Dust	95	2	.04	5	.09
9	Mercury C	87	3	.06	29	.55
10	Bayer 171–A	86	45	.94	161	3.05
11	Paraformaldehyde	85	115	2.40	553	10.50
12	Germisan (0.25 per cent, 1 hour)	83	0	0	1	.02

In the controls from 1925 and 1926 seed, the number of stripe-diseased plants averaged 5.2 per cent and 12.9 per cent, respectively. Höchst again was outstanding in its complete control of stripe disease in all replications, as also was the Du Pont Dust K–1–C. The essential ingredient of the latter dust consisted of 1.5 per cent of ethyl mercuric chloride. K–1–D contained only 1 per cent of this chemical, and, as will be observed in Table 23, it was on the border line of complete effectiveness. A product similar to K–1–C, but containing 2 per cent of ethyl mercuric chloride, is now on the market under the

trade name of Ceresan. Next in the order of effectiveness came Germisan (0.25 per cent solution), Wa Wa Dust, Mercury C, and Abavit B. The remaining dusts were relatively ineffective, as none of them reduced the infection in the plants from 1926 seed to less than 1 per cent.

In order to determine whether the more efficient treatments caused any consistent increases in the yield of grain, the different replications were harvested and each 2-row replication was threshed separately in a plot thresher. The average yields per replication are presented in Table 22, together with the average increase in yield caused by each treatment. With 5.2 per cent of stripe disease in the controls from 1925 seed, and less than 0.2 per cent of infection in any of the rows from treated seed, the different treatments seemed to cause an increase in yield of from 0.2 per cent in the case of K–1–D to 16.1 per cent in the case of Abavit B. Only in the case of Abavit B and Germisan, however, were the increases in yield significant on the basis of the odds calculated according to Student's method.

TABLE 22.—*Percentage of stripe-diseased plants in and yield from Wisconsin Pedigree No. 6 barley grown from two lots of naturally inoculated seed, untreated or treated with various seed disinfectants, and sown at Madison, Wis., April 26, 1928, in paired rod rows replicated twelve times for each treatment and each seed lot*

1925 SEED

Seed treatment		Stripe-diseased plants	Average replication yield	Increase in yield as compared with control		
No.	Name					
		Per cent	*Grams*	*Grams*	*Per cent*	*Odds*
	Control (untreated)	5.20	614			
1	Abavit B	.13	713	99	16.1	638:1
3	Höchst	0	672	58	9.4	8:1
6	Du Pont K–1–C	0	662	48	7.8	18:1
7	Du Pont K–1–D	.02	615	1	.2	1:1
8	Wa Wa Dust	.04	631	17	2.8	2:1
9	Mercury C	.06	655	41	6.7	12:1
12	Germisan	0	689	75	12.2	68:1

1926 SEED

	Control (untreated)	12.9	551			
1	Abavit B	.87	647	96	17.4	93:1
3	Höchst	0	644	93	16.9	160:1
6	Du Pont K–1–C	0	652	101	18.3	21:1
7	Du Pont K–1–D	0	740	189	34.3	207:1
8	Wa Wa Dust	.09	641	90	16.3	1,221:1
9	Mercury C	.55	633	82	14.9	15:1
12	Germisan	.02	685	134	24.3	188:1

In the control rows from the 1926 seed the stripe disease averaged 12.9 per cent, while the average infection for the treated seed was 0.22 per cent. Five of the seven treatments compared caused significant increases in yield of from 16.3 per cent to 34.3 per cent, the average increase for all treatments being 20.3 per cent.

EXPERIMENTS IN 1929

Experiments begun in the fall of 1928 and designed to test the efficiency of certain fungicides in the control of smuts in Tennessee Winter and Wisconsin Winter barleys yielded some data on the control of stripe disease in these varieties the following spring. Seven

dust fungicides had been used together with a 1:320 solution of 37 per cent formaldehyde for comparison. The dusts had been applied to the seed at the rate of 3 ounces per bushel. The formaldehyde treatment had been applied as follows: The seed was soaked in water for 15 minutes and then was allowed to lie covered for four hours. After a 20-minute immersion in the 1:320 formaldehyde solution it was again covered for three hours and then dried with a fan. The seed was sown October 18, 1928, in soil that was only 19 per cent saturated. This lack of ample soil moisture seems to be reflected in the relatively poor control of stripe disease by some of the dusts, as shown by the data which were taken in May, 1929, presented in Table 23.

TABLE 23.—*Stripe-diseased plants in Tennessee Winter and Wisconsin Winter barley grown from seed, untreated or treated with different fungicides, and sown in rod rows replicated eight times for each treatment and control in each variety, Arlington Experiment Farm, Rosslyn, Va., October 18, 1928*

Seed treatment		Stripe-diseased plants			
No.	Name	Tennessee Winter		Wisconsin Winter	
		Number	*Per cent*	*Number*	*Per cent*
	Control (untreated)	101	5.10	21	1.05
1	Ceresan	1	.05	1	.05
2	Bayer P. M. A	6	.30	0	0
3	Höchst	15	.75	1	.05
4	Abavit B	27	1.35	7	.35
5	Formaldehyde	9	.45	3	.15

Experiments on the control of stripe disease in two varieties of spring barley in 1929 were restricted to seven dust fungicides and one liquid fungicide. Seed of Wisconsin Pedigree No. 5 was used in an experiment of rather limited scope designed primarily to test several dust fungicides as to their efficiency in loose-smut control. However, more stripe disease than loose smut developed; therefore, data were taken on the control of this disease, as shown in Table 24. Ceresan, Bayer P. M. A., and Höchst gave perfect control, and Mercury C was very good, but Abavit B, which had been consistently effective in previous experiments, gave only about 50 per cent control in series 1, although in the more limited replications of series 2 it permitted only one stripe-diseased plant. The Abavit B used in series 1 came from a container that had been partly open since the preceding October, while that used in series 2 came from a sealed container. This may account for the different results obtained in the two series. Corona 80–B and Smuttox proved relatively worthless as fungicides for stripe-disease control. Germisan, the liquid fungicide, proved effective, as usual.

Naturally inoculated seed of Wisconsin Pedigree No. 6 barley was used in 1929 in rather extensive field experiments carried out at a number of experiment stations in addition to the Arlington Experiment Farm. The seed was treated at the Arlington farm February 27, 1929, 3 ounces per bushel being used in the case of each of the dust fungicides. The Germisan treatment, as usual, consisted of a 1-hour soak at room temperature in a 0.25 per cent water solution of Germisan, after which the seed was thoroughly dried.

TABLE 24.—*Stripe-diseased plants in Wisconsin Pedigree No. 5 barley grown from seed, untreated or treated with different fungicides, and sown at Arlington Experiment Farm, Rosslyn, Va., in two series*

[Series 1, sown March 13 in quadruplicated rod rows in soil 46 to 50 per cent saturated and with an average temperature of 11.5° C. during the period of emergence; series 2, sown April 6 in paired rod rows in soil 75 per cent saturated, with a rainfall of 1.2 inches and an average soil temperature of 16.1° during the period of emergence]

Seed treatment		Stripe-diseased plants			
No.	Name	Series 1		Series 2	
		Number	*Per cent*	*Number*	*Per cent*
	Control (untreated)	182	22.3	31	5.8
1	Ceresan	0	0	0	0
2	Bayer P. M. A	0	0	0	0
3	Höchst	0	0	0	0
4	Abavit B	68	10.1	1	.2
	Control (untreated)	138	21.8	21	4.4
5	Mercury C	5	.6	2	.4
6	Corona 80-B	127	14.8	24	4.4
7	Smuttox	172	19.7	13	2.4
8	Germisan	0	0	0	0

The untreated and treated seed was packeted and sent to the different stations for sowing. The following are the stations and the workers whose cooperation made this work possible:

Arlington Experiment Farm, Rosslyn, Va.
Manhattan, Kans.; C. O. Johnston.
North Platte, Nebr.; G. F. Sprague.
Madison, Wis.; J. G. Dickson.
Brookings, S. Dak.; K. H. Klages.
St. Paul, Minn.; C. S. Holton.
Fargo, N. Dak.; W. E. Brentzel.
Dickinson, N. Dak.; R. W. Smith.

TABLE 25.—*Stripe-diseased plants in Wisconsin Pedigree No. 6 barley, grown from seed untreated or treated with different fungicides and sown in rod rows replicated four times for each treatment and control at each of eight stations* [1] *in 1929, and data on the length of, and environmental conditions during, the period of emergence*

Seed treatment		Percentage of stripe-diseased plants at station No.— [1]								Total infected plants	
No.	Name	1	2	3	4	5	6	7	8		
										Number	*Per cent*
	Control (untreated)	7.7	1.4	12.7	8.1	10.7	4.5	3.0	4.1	522	6.5
1	Ceresan	0	0	0	0	0	0	0	0	0	0
2	Bayer P. M. A	0	0	0	0	0	0	0	0	0	0
3	Höchst	0	0	0	0	0	0	0	0	0	0
4	Abavit B	0	0	.8	.1	.2	0	0	0	11	.14
	Control (untreated)	5.4	1.4	13.6	6.8	8.5	4.2	2.8	3.2	462	5.6
5	Mercury C	0	0	.7	.1	.2	.1	0	0	11	.14
6	Corona 80-B	4.7	1.4	14.0	5.6	5.4	3.0	4.3	2.5	416	5.0
7	Smuttox	6.1	2.0	13.4	5.3	4.5	3.7	5.0	2.9	447	5.4
8	Germisan (0.25 per cent, 1 hour)	0	0	0	0	0	0	0	0	0	0
	Items	Other data for stations numbered as above									
	Time to emerge.....days	11	16	23	13	13	13	17	13		
	Soil moisture: [2]										
	At sowing	15	11	20	15	([3])	24	12	20		
	At emergence	20	([3])	25	13	([3])	24	([3])	18		
	Mean soil temperature.....° C.	12	12	10	9	[4] 7	9	4	3		
	Rainfall.....inches	.44	.72	3.30	.74	.05	.41	1.40	.09		

[1] Stations at: 1, Rosslyn, Va.; 2, Manhattan, Kans.; 3, North Platte, Nebr.; 4, Madison, Wis.; 5, Brookings, S. Dak.; 6, St. Paul, Minn.; 7, Fargo, N. Dak.; 8, Dickinson, N. Dak.

[2] Expressed as percentage of saturation. [3] Moist; no soil test made. [4] Air temperature.

At each station the seed was sown in rod rows replicated four times for each treatment and control. The stripe-disease data taken later in the season are summarized in Table 25, together with data relating to environmental conditions during the period of emergence at each station. A study of the latter data fails to show any consistent correlation between any set of environmental conditions recorded there and the development or the control of stripe disease.

As in a number of previous experiments, Ceresan, Höchst, Bayer P. M. A., and Germisan controlled stripe disease completely, while Abavit B and Mercury C reduced its occurrence to a small trace. Corona 80–B and Smuttox failed entirely to qualify as fungicides for stripe-disease control. In several cases more stripe disease occurred where these compounds were used than was found in the corresponding controls.

EXPERIMENTS IN 1930

During the winter of 1929–30, different commercial concerns sent a number of new fungicidal dusts to be tested for their value in the control of various cereal diseases. These were, accordingly, included in experiments for the control of stripe disease, together with several other fungicidal dusts that had been used in previous experiments.

Five lots of spring barley were used in the experiments: Lot A, Wisconsin Pedigree No. 5, and lot B, Wisconsin Pedigree No. 6, both grown in 1928 at the Wisconsin Agricultural Experiment Station; lot C, Minnesota Velvet, grown in 1929 on the farm of N. Y. Keenan, Oregon, Wis.; and lots D and E, unknown varieties grown in 1929 near Waukesha, Wis.

The different dust fungicides were applied to the seed March 8, 1930, at the rate of 3 ounces per bushel, while the Germisan treatment was carried out as in previous experiments. To determine the effect of the treatments on germination, seed of each of the first three lots of barley, lots A, B, and C, treated with each of the fungicides was sown in the greenhouse bench. The data on germination, taken 10 days later, are given in Table 26. It will be noted that none of the treatments seemed to exert any injurious effect upon germination.

TABLE 26.—*Germination percentages of lots A, B, and C of spring barleys grown from untreated and treated seed sown March 19, 1930, in the greenhouse, Arlington Experiment Farm, Rosslyn, Va.*

Seed treatment		Percentage of germination			Average
No.	Name	Lot A	Lot B	Lot C	
					Per cent
	Control (untreated)	78	93	95	88.9
1	Ceresan	82	92	98	91.0
2	Dubay No. 655	78	95	97	90.0
3	Dubay No. 665	87	96	97	93.3
4	Abavit B	83	96	96	91.6
	Control (untreated)	83	91	96	90.0
5	Höchst	81	96	99	92.0
6	Wa Wa Dust	83	84	95	87.3
7	Corona Oat Dust	86	83	96	88.3
8	Sterocide	79	90	96	88.3
	Control (untreated)	85	83	92	86.6
9	Sanoseed Grain Dust	75	88	98	87.0
10	Acco Dust No. 7	86	90	98	91.3
11	Wienert's Compound	85	94	88	89.0
12	Germisan	86	92	99	92.3

Untreated and treated seed of all five lots of barley, lots A, B, C, D, and E, was sown on the Arlington Experiment Farm in paired rod rows in four parallel series. Each series was sown on a different date and on a different part of the farm, in order to secure different environmental conditions. The salient facts regarding the dates of sowing, the length of the periods from sowing to emergence, and the environmental conditions during these periods are shown in Table 27. Unfortunately, sudden inclement weather interrupted the work of sowing series 1 so that it was not possible to include seed of lots D and E in this series.

TABLE 27.—*Environmental data on experiments for the control of stripe disease in five lots of spring barley sown on Arlington Experiment Farm, Rosslyn, Va., 1930*

Series No.	Date sown	Days to emerge	Average soil temperature [1]	Moisture content [2] of soil		Rainfall [1]
				At sowing	At emergence	
			° C.			*Inches*
1	Mar. 11	19	5	67	56	1.01
2	Mar. 17	18	6	58	56	.65
3	Mar. 18	17	6.5	70	50	.65
4	Mar. 20	16	7.5	40	39	.98

[1] From sowing to emergence. [2] Expressed as percentage of water-holding capacity.

Untreated and treated seed of lots A, B, and C was sown also at Madison, Wis., April 25, and the seedlings emerged May 3. A second sowing of seed of lot A was made at Madison, Wis., April 30, and the seedlings emerged May 6. In each case only two rod rows were sown for each treatment and each seed lot.

The stripe-disease data taken at the Arlington Experiment Farm and at Madison, Wis., are presented in Tables 28 and 29, respectively. At the former place, stripe disease was completely eliminated in all replications only by Dubay No. 665 and Corona Oat Dust.[7] However, it was reduced to a general average of less than 0.1 per cent by Ceresan, Dubay No. 655, Höchst, and Germisan, the total number of stripe-diseased plants in all four series being 2, 1, 2, and 3, respectively, as compared with an average of slightly over 900 stripe-diseased plants in corresponding control rows. Abavit B, Wa Wa Dust, and Wienert's Compound, while fairly effective on the whole, were not consistently effective, for in certain replications they permitted the occurrence of more than 1 per cent of stripe-diseased plants. Sterocide, Sanoseed Grain Dust, and Acco Dust No. 7 yielded, on the whole, very unsatisfactory results.

[7] It should be stated that in 1930 this dust contained ethyl mercuric chloride, to which doubtless may be attributed its effectiveness in this case. At present this compound does not contain this ingredient and is not recommended for stripe-disease control.

TABLE 28.—*Percentage of stripe-diseased plants in five lots of barley grown from untreated or treated seed sown in paired rod rows in four series, March 11, 17, 18, and 20, 1930, respectively, Arlington Experiment Farm, Rosslyn, Va.*

No.	Seed treatment	Percentage of stripe-diseased plants in—														
		Lot A					Lot B					Lot C				
		Series No.				Average	Series No.				Average	Series No.				Average
	Name	1	2	3	4		1	2	3	4		1	2	3	4	
	First control (untreated)	17.2	21.0	16.6	34.8	22.8	4.3	8.6	6.4	4.0	5.7	10.7	13.2	4.7	6.5	8.9
1	Ceresan	0	0	0	0	0	0	.4	0	0	.1	0	0	0	0	0
2	Dubay No. 655	0	0	0	0	0	.2	0	0	0	.1	0	0	0	0	0
3	Dubay No. 665	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Abavit B	1.0	.4	0	0	.4	.2	0	0	0	.1	1.8	0	0	0	.5
	Second control (untreated)	16.1	22.0	13.9	33.0	21.2	5.6	7.4	6.9	2.4	5.5	10.9	11.4	8.8	7.0	9.6
5	Höchst	0	0	0	0	0	0	0	0	0	0	0	0	.2	0	[1] T
6	Wa Wa Dust	1.4	3.6	2.0	.2	1.8	.2	.2	0	0	.1	3.7	1.6	0	0	1.4
7	Corona Oat Dust	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Sterocide	16.4	16.4	9.2	15.1	14.2	4.0	.6	.9	.9	1.6	7.4	0	.6	0	1.9
	Third control (untreated)	19.3	20.3	18.5	25.7	20.9	6.0	7.3	6.0	3.8	5.9	10.8	13.0	5.4	9.5	9.9
9	Sanoseed Grain Dust	16.3	9.6	11.3	5.3	10.4	.5	.8	.9	.2	.7	1.8	2.0	.6	.2	1.2
10	Acco Dust No. 7	20.0	21.0	17.6	22.7	20.3	4.8	8.3	3.5	6.7	5.9	5.8	6.1	2.6	.6	4.0
11	Wienert's Compound	2.3	.6	.4	0	.8	0	0	0	0	0	.6	0	0	0	.1
12	Germisan (0.25 per cent, 1 hour)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

No.	Seed treatment	Percentage of stripe-diseased plants in—Continued										Total stripe-diseased plants	
		Lot D [2]					Lot E [2]						
		Series No.				Average	Series No.				Average		
	Name	1	2	3	4		1	2	3	4		No.	*Per cent*
	First control (untreated)	.....	15.4	1.4	10.5	10.3	.....	6.8	1.7	1.6	3.3	900	10.4
1	Ceresan	.....	0	0	0	0	.....	0	0	0	0	2	T
2	Dubay No. 655	.....	0	0	0	0	.....	0	0	0	0	1	T
3	Dubay No. 665	.....	0	0	0	0	.....	0	0	0	0	0	0
4	Abavit B	.....	0	0	0	0	.....	0	0	0	0	19	.2
	Second control (untreated)	.....	10.5	3.3	14.2	10.1	.....	6.6	3.0	1.8	3.9	912	10.27
5	Höchst	.....	0	0	0	0	.....	0	.2	0	.1	2	T
6	Wa Wa Dust	.....	0	0	0	0	.....	.4	0	0	.1	70	.8
7	Corona Oat Dust	.....	0	0	0	0	.....	0	0	0	0	0	0
8	Sterocide	.....	4.6	.7	1.3	2.5	.....	3.1	.8	0	1.3	371	4.34
	Third control (untreated)	.....	12.3	4.3	10.4	9.4	.....	6.3	2.9	2.6	3.9	894	10.2
9	Sanoseed Grain Dust	.....	.8	2.3	.4	1.0	.....	.9	.8	0	.5	249	2.8
10	Acco Dust No. 7	.....	6.4	1.1	5.6	4.7	.....	3.3	1.7	1.2	2.0	664	7.6
11	Wienert's Compound	.....	0	0	0	0	.....	0	0	0	0	17	.2
12	Germisan (0.25 per cent, 1 hour)	.....	.2	0	.4	.2	.....	0	0	0	0	3	T

[1] T=trace, or less than 0.1 per cent.
[2] Unknown varieties from Waukesha, Wis.

In general, the results obtained at Madison, Wis., were similar to those obtained at the Arlington farm, except that instead of only two, five dusts, namely, Ceresan, Dubay No. 655, Dubay No. 665, Höchst, and Corona Oat Dust, as well as the Germisan liquid treatment, completely eliminated stripe disease. Wa Wa Dust and Wienert's Compound were slightly more effective at Madison, Wis., than at the Arlington farm, while Sterocide, Sanoseed Grain Dust, and Acco Dust No. 7, as before, were entirely unsatisfactory from the standpoint of stripe-disease control. The results from Abavit B were identical at both places.

TABLE 29.—*Percentage of stripe-diseased plants in three lots of barley grown from untreated or treated seed sown in paired rod rows at Madison, Wis., April, 1930*

No.	Seed treatment	Stripe-diseased plants in—				Total stripe-diseased plants	
		Wisconsin Pedigree No. 5		Wisconsin Pedigree No. 6	Minnesota Velvet		
	Name	Series 1	Series 2				
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Number*	*Per cent*
	First control (untreated)	12.0	13.8	2.1	0.9	113	7.2
1	Ceresan	0	0	0	0	0	0
2	Dubay No. 655	0	0	0	0	0	0
3	Dubay No. 665	0	0	0	0	0	0
4	Abavit B	.2	.3	0	.2	3	.2
	Second control (untreated)	13.6	8.0	4.6	2.3	144	7.0
5	Höchst	0	0	0	0	0	0
6	Wa Wa Dust	0	.6	0	0	2	.1
7	Corona Oat Dust	0	0	0	0	0	0
8	Sterocide	9.7	9.3	1.8	.2	89	4.6
	Third control (untreated)	13.7	10.7	4.6	2.5	150	7.6
9	Sanoseed Grain Dust	4.5	6.9	.2	.5	57	2.7
10	Acco Dust No. 7	13.8	11.0	2.6	3.2	135	7.2
11	Wienert's Compound	.4	1.0	.6	0	8	.4
12	Germisan (0.25 per cent, 1 hour)	0	0	0	0	0	0

DISCUSSION

In the five years from 1926 to 1930, inclusive, more than 75 fungicidal dusts were used in experiments on the control of stripe disease. Only one of these, namely, Abavit B, was included in experiments covering this entire period. Three of the dusts were tested over a period of four years, six were tried for three years, eight for two years, and the remainder were used in only one year's experiments. A number of previously untried experimental dusts received from different companies or individuals, as well as some made up in the laboratory, were limited to tests in preliminary greenhouse experiments, in which their injurious effects upon seed germination or their other objectionable features furnished sufficient reasons for promptly discarding them. No mention is made of these dusts in the foregoing pages.

Eight dusts were received from Germany and one from France. None of these has ever been on the market in the United States.

More than 50 dusts were submitted by different individuals or commercial concerns in the United States. Most of these were experimental dusts and never reached the stage of commercial manufacture. Many were discarded as ineffective after one or two trials. The formulae of some, however, with slight modifications have been more recently used in the manufacture of very effective fungicides.

Of the 21 or more dusts made up from materials in the laboratory, none proved very promising. A few were effective in stripe-disease control, but seriously injured germination and stand.

A representative number of the dusts that were tested are listed in Table 30, which shows the number of seasons each dust was tested, the total number of rod rows devoted to each during this period, the number of stripe-diseased plants found in these rows and also in an equal number of rows from untreated seed, and finally, the degree of control obtained by using each dust.

TABLE 30.—*Relative efficiency of a number of fungicidal dusts in the control of stripe disease in barley in experiments covering from one to five years, the liquid fungicide Germisan being included for comparison*

Treatment		Seasons tested	Rod-row replications	Infected plants from—		Average control
No.	Name			Untreated seed	Treated seed	
		Number	*Number*	*Number*	*Number*	*Per cent*
	Germisan (liquid)	5	208	3,747	5	99.9
1	Abavit B	5	342	7,146	239	96.7
2	Höchst	4	236	4,762	20	99.6
3	Wa Wa Dust	4	296	6,466	94	98.6
4	Mercury C	4	242	4,663	111	97.6
5	Ceresan	3	114	2,575	4	99.8
6	S. F. A. No. 225–V	3	244	4,536	145	96.8
7	Semesan	3	252	5,281	184	96.5
8	Bayer Dust	3	192	3,781	148	96.1
9	Semesan Jr	3	204	3,899	180	95.4
10	S. F. A. No. 226	3	106	1,652	120	92.7
11	Du Pont No. 35	2	24	501	6	98.8
12	Du Pont No. 45	2	92	1,829	44	97.6
13	Du Pont No. 64	2	24	711	29	95.9
14	Tutan	2	166	3,340	279	91.7
15	Du Pont No. 53	2	24	711	101	85.8
16	Vitrioline	2	8	152	33	78.3
17	S. I. No. 220	2	140	2,297	680	70.4
18	Du Pont No. 68	2	8	149	62	58.4
19	Corona Oat Dust [1]	1	42	1,062	0	100.0
20	Dubay No. 665	1	42	900	0	100.0
21	Dubay No. 655	1	42	900	1	99.9
22	Bayer P. M. A	1	46	857	6	99.3
23	Abavit No. 1394	1	4	80	1	98.8
24	Bayer No. 189	1	4	77	1	98.7
25	Wienert's Dust	1	42	1,062	25	97.7
26	Bayer Dust II	1	122	1,588	64	96.0
27	Du Pont No. 57	1	4	73	5	93.2
28	Agfa No. 331	1	4	83	8	90.4
29	Karasch A	1	4	72	7	90.3
30	Bayer No. 171–A	1	24	653	161	75.3
31	Sanoseed Grain Dust	1	42	1,062	306	71.2
32	Sterocide	1	46	1,070	460	57.0
33	Copper oxychloride	1	4	80	57	28.8
34	Iodin, 5 per cent	1	4	73	53	27.4
35	Paraformaldehyde, 25 per cent	1	48	893	668	25.2
36	Acco Dust No. 7	1	42	1,062	799	24.8
37	Corona 80–B	1	38	675	567	16.0
38	Cuprobol	1	4	72	66	8.3
39	Smuttox	1	38	675	632	6.3
40	Formaldehyde dust, 6 per cent	1	4	80	75	6.3

[1] Contained 0.75 per cent of ethyl mercuric chloride. The Corona Oat Dust now on the market does not contain ethyl mercuric chloride.

The figure for control was obtained as follows:

$$\left(1-\frac{\text{diseased plants from treated seed}}{\text{diseased plants from untreated seed}}\right)\times 100$$

the result, of course, being expressed in terms of percentage. The significance of this figure is, of course, largely governed by the number of replications, as well as by the number of seasons covered by the tests. Similar data are given for the liquid treatment, Germisan, which was used for comparison in many of the experiments.

Taking into consideration the number of seasons in which they were tested and the number of replications used, as well as the percentage control, shown in Table 34, the two most effective dust fungicides were Ceresan and Höchst. Abavit B, the most extensively tested dust fungicide, was somewhat lacking in consistent effectiveness, as were also Mercury C, Wa Wa Dust, and a number of others. Among those tested for two seasons, Du Pont No. 35 was most efficient, and its formula is now used in the manufacture of a seed-corn disinfectant.

Corona Oat Dust,[8] Dubay No. 655, and Dubay No. 665 were the most effective dust fungicides among those used in only one season's tests. The two latter are slight modifications of Ceresan. Bayer P. M. A. was effective in stripe-disease control, but was somewhat injurious to germination. Abavit 1394 and Bayer 189 were promising in a very limited number of replications.

SUMMARY

Stripe disease is practically coextensive with barley culture. The losses caused by it emphasize the desirability of its prevention by seed treatment or by growing resistant varieties.

Stripe disease is caused by *Helminthosporium gramineum* Rabh. and should not be confused with net blotch caused by *H. teres* nor spot blotch caused by *H. sativum*.

Kernels of healthy heads become inoculated by spores blown from near-by diseased plants. These spores become lodged between the glume and the pericarp of the seed, where they germinate and give rise to mycelium, which lies dormant there until the seed germinates. This mycelium then revives and infects the emerging coleoptile, which in turn carries the infection to the next leaf. Successively emerging leaves are infected in turn, and finally the head, which commonly does not emerge completely and seldom produces viable seeds.

Natural inoculation of kernels in the field by wind-borne spores may occur for a considerable period after flowering.

Under some conditions, spores on the outside of the seed may produce infection in the seedling, but it is generally conceded that dormant mycelium is the principal means of the fungus living over from one crop to another.

Removing the glumes from naturally inoculated kernels before sowing had no effect on the percentage of stripe-diseased plants.

Conidia may remain viable from 3½ to 34 months, according to different investigators. Longevity is undoubtedly contingent on conditions of temperature and moisture during storage of the spore material.

Dormant mycelium in the seed remains viable for at least five years.

Viable seeds from diseased plants are not the rule; yet they are not uncommon.

Increased soil fertility or any other condition favoring vigorous plant growth apparently decreases the percentage of diseased plants from naturally inoculated seed.

Growing temperatures of 15° C., or below, during the period of emergence favor the development of the disease in plants from naturally inoculated seed. Temperatures above 20° C. during that period tend to inhibit the development of the disease. Likewise, relatively dry soil (less than 40 per cent saturated) during germination is more conducive to stripe-disease development than extremely wet soil (approximately 90 per cent saturated).

During the 5-year period 1926–1930, more than 75 fungicidal dusts were tested in stripe-disease control experiments. The effectiveness of the dust fungicides used was found to be independent of soil reaction

[8] This lot contained 0.75 per cent of ethyl mercuric chloride.

and of soil moisture except when the latter was less than 25 per cent of saturation, in which case the effectiveness of the fungicides was reduced. In experiments in which yield data were obtained, the average percentage increase in yield from seed treated with certain fungicides over that from untreated seed invariably was greater than the percentage of stripe-diseased plants from untreated seed observed at the time of heading. This additional increase in yield probably was due to the control of other unobserved diseases, as well as to the control of stripe disease to a greater extent than was indicated by the percentage of stripe disease found in the plants from untreated seed at the time the data were taken.

Although the ordinary wet formaldehyde treatment controls stripe disease satisfactorily, formaldehyde dusts were found ineffective for this purpose.

LITERATURE CITED

(1) ANONYMOUS.
1919. LEAF STRIPE OF BARLEY IN SCOTLAND. Scot. Jour. Agr. 2: 535–536.

(2) CHABROLIN, C.
1927. QUELQUES MALADIES DES PLANTES CULTIVÉES EN TUNISIE. Dir. Gén. Agr. Com. et Colon. [Tunis] Bul. 31:41–59, illus.

(3) DORPH-PETERSEN, K.
1927. BERETNING FRA STATSFRØKONTROLLEN FOR DET 55. ARBEJDSAAR FRA 1. JULI 1925 TIL 30. JUNE 1926. Tidsskr. Planteavl 33:1–83.

(4) DRECHSLER, C.
1923. SOME GRAMINICOLOUS SPECIES OF HELMINTHOSPORIUM: I. Jour. Agr. Research 24:641–740, illus.

(5) FUCHS, W.
1930. EINE NEUE METHODE ZUR KÜNSTLICHEN INFEKTION DER GERSTE MIT HELMINTHOSPORIUM GRAMINEUM RABH. UND IHRE ANWENDUNG ZUR PRÜFUNG VON BEIZ- UND IMMUNITÄTSFRAGEN. Phytopath. Ztschr. 2:[235]–256.

(6) GENAU, A.
1928. METHODEN DER KÜNSTLICHEN INFEKTION DER GERSTE MIT HELMINTHOSPORIUM GRAMINEUM UND STUDIEN ÜBER DIE ANFÄLLIGKEIT VERSCHIEDENER SOMMERGERSTEN DIESEM PILZ GEGENÜBER. Kühn Arch. 19:[303]–351.

(7) GESCHELE, E. E.
1927. BEHAVIOR OF VARIETIES OF BARLEY IN REGARD TO ATTACKS BY HELMINTHOSPORIUM TERES. Abstract in Ann. Stats. Inst. Expt. Agron. Leningrad 5:202. [Title in Russian.]

(8) GISEVIUS and STRAIB.
1926. ZUR BEKÄMPFUNG DER STREIFENKRANKHEIT DER GERSTE, INSBESONDERE DURCH TROCKENBEIZE. Deut. Landw. Presse 53: 398–399, illus.

(9) GRAM, E., JØRGENSEN, C. A., and ROSTRUP, S.
1928. OVERSIGT OVER SYGDOMME HOS LANDBRUGETS KULTURPLANTER I 1927. Tidsskr. Planteavl 34:778–836.

(10) ——— and ROSTRUP, S.
1924. PLANT DISEASES AND PESTS IN DENMARK 1923. Tidsskr. Planteavl 30:361–414. [In Danish. English summary, p. 412–414.]

(11) ——— and THOMSEN, M.
1927. PLANT DISEASES AND PESTS IN DENMARK 1925. Tidsskr. Planteavl 33:84–148. [In Danish. English summary, p. 146–148.]

(12) HOWITT, J. E., and STONE, R. E.
1928. RESULTS OF EXPERIMENTS ON THE CONTROL OF BARLEY STRIPE. (Abstract) Phytopathology 18:477–478.

(13) ISENBECK, K.
1930. UNTERSUCHUNGEN ÜBER HELMINTHOSPORIUM GRAMINEUM RABH. IN RAHMEN DER IMMUNITÄTSZÜCHTUNG. Phytopath. Ztschr. 2:[503]–555.

(14) JOHNSON, T.
1925. STUDIES ON THE PATHOGENICITY AND PHYSIOLOGY OF HELMINTHOSPORIUM GRAMINEUM RAB. Phytopathology 15:[797]–804.

(15) KIESSLING, L.
1917. ÜBER DIE SPEZIFISCHE EMPFINDLICHKEIT DER GERSTE GEGENÜBER DER STREIFENKRANKHEIT. Ztschr. Pflanzenzücht. 5:31–40.
(16) LEUKEL, R. W.
1924. EQUIPMENT AND METHODS FOR STUDYING THE RELATION OF SOIL TEMPERATURE TO DISEASES IN PLANTS. Phytopathology 14: [384]–397, illus.
(17) ———
1930. SEED TREATMENT FOR CONTROLLING COVERED SMUT OF BARLEY. U. S. Dept. Agr. Tech. Bul. 207, 23 p., illus.
(18) ——— DICKSON, J. G., and JOHNSON, A. G.
1926. SEED TREATMENT EXPERIMENTS FOR CONTROLLING STRIPE DISEASE OF BARLEY. Phytopathology 16:565–576.
(19) ——— DICKSON, J. G., and JOHNSON, A. G.
1927. EXPERIMENTS WITH DUSTS FOR CONTROLLING STRIPE DISEASE OF BARLEY. Phytopathology 17:175–179.
(20) LINDFORS, T.
1927. BETNINGSMEDEL FÖR VÅRSÄDEN. [DISINFECTANTS FOR SPRING SEED-GRAIN.] Landtmannen 10:182–183, illus. (Abstract in Rev. Appl. Mycol. 6:544–545. 1927.)
(21) MOLZ, E.
1926. NEUE ERFAHRUNGEN MIT DER TROCKENBEIZE DES SAATGUTES. Deut. Landw. Presse 53: 425–426.
(22) NISIKADO, Y.
1929. STUDIES ON THE HELMINTHOSPORIUM DISEASES OF GRAMINEAE IN JAPAN. Ber. Ōhara Inst. Landw. Forsch. 4:111–126, illus.
(23) NOVÁK, S.
1926. NĚKOLIK POZNÁMEK O PRUHOVITOSTI JEČMENE. (PŘEDBĚŽNÁ PRÁVA.) [SOME NOTES ON THE STRIPE DISEASE OF BARLEY.] Ochrana Rostlin 6:83–85. (Abstract in Rev. Appl. Mycol. 6:222. 1927.)
(24) ———
1926. O PRUHOVITOSTI JEČMENE. [STRIPE DISEASE OF BARLEY.] Ochrana Rostlin 6:33–36, illus. (Abstract in Rev. Appl. Mycol. 6:221. 1927.)
(25) PLAUT, M.
1926. BEIZ- UND STIMULATIONSVERSUCHE MIT ZUCKERRÜBENSAMEN UND GETREIDE. Ztschr. Pflanzenkrank. 36:[321]–351, illus.
(26) POETEREN, N. VAN.
1922. VERSLAG OVER DE WERKZAAMHEDEN VAN DEN PLANTENZIEKTENKUNDIGEN DIENST IN DE JAREN 1920 EN 1921. Verslag. en Meded. Plantenziektenkund. Dienst. Wageningen 27, 92 p., illus. (Abstract in Rev. Appl. Mycol. 2:52–54. 1923.)
(27) PORTER, R. H., YU, T. F., and CHEN, H. K.
1929. THE RESPONSE OF HULLESS BARLEY TO SEED TREATMENT FOR COVERED SMUT AND STRIPE DISEASE. Phytopathology 19: 657–666.
(28) RAVN, F. K.
1900. NOGLE HELMINTHOSPORIUM-ARTER OG DE AF DEM FREMKALDTE SYGDOMME HOS BYG OG HAVRE. Bot. Tidsskr. 23:101–321, illus.
(29) REDDY, C. S., and BURNETT, L. C.
1930. DEVELOPMENT OF SEED TREATMENTS FOR THE CONTROL OF BARLEY STRIPE. Phytopathology 20:367–390.
(30) RIEHM, E.
1921. ÜBER DIE HELMINTHOSPORIEN DER GERSTE. Mitt. Biol. Reichanst. Land u. Forstw. 16 (Mitt. 21): 43–45.
(31) RIPPEL, A., and LUDWIG, O.
1927. ÜBER DEN EINFLUSS DES ERNÄHRUNGSZUSTANDES DER GERSTE AUF DEM BEFALL DURCH PLEOSPORA TRICHOSTOMA WINT. (STREIFENKRANKHEIT.) Angew. Bot. 9:541–560, illus.
(32) RODENHISER, H. A.
1928. EXPERIMENTS ON THE CONTROL OF BARLEY STRIPE. Phytopathology 18:295–300.
(33) SINNING, A.
1927. EIGNET SICH DIE TROCKENBEIZE EBENSOGUT WIE DIE NASSBEIZE ZUR BEKÄMPFUNG ALLER GETREIDEKRANKHEITEN? Deut. Landw. Presse 54:546, illus.

(34) SINNING, A.
1929. VERSUCHE MIT TROCKENBEIZEN GEGEN DIE STREIFENKRANKHEIT DER GERSTE. Deut. Landw. Presse 56:183.
(35) SMITH, N. J. G.
1929. OBSERVATIONS OF THE HELMINTHOSPORIUM DISEASES OF CEREALS IN BRITAIN. Ann. Appl. Biol. 16:236–260.
(36) ——— and RATTRAY, J. M.
1930. NETBLOTCH, SPOTBLOTCH, AND LEAF-STRIPE DISEASES OF BARLEY IN SOUTH AFRICA. So. African Jour. Sci. 27:341–351, illus.
(37) STRAIB.
1927. ERTRAGSAUSFÄLLE DURCH STREIFENKRANKHEITEN BEI SOMMERGERSTE. Deut. Landw. Presse 54:176.
(38) VOGT, E.
1923. EIN BEITRAG ZUR KENNTNIS VON HELMINTHOSPORIUM GRAMINEUM RBH. Arb. Biol. Reichsanst. Land u. Forswt. 11: [387]–397, illus.
(39) WAHL, B.
1926. BERICHT ÜBER DIE TÄTIGKEIT DER BUNDESANSTALT FÜR PFLANZENSCHUTZ IN WIEN IM JAHRE 1925. Verslag. Bundesanst. Pflanzenschutz Wien 11, 28 p. [Ztschr. Landw. Versuchsw. Deutsch-österr. 28:21–48.]
(40) WINKELMAN, A.
1929. INFECTIONSVERSUCHE MIT HELMINTHOSPORIUM GRAMINEUM. Angew. Bot. 11:120–126.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Horticultural Crops and Diseases	E. C. AUCHTER, *Principal Horticulturist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 340 FEBRUARY, 1933

DISTINCTIVE EFFECTS OF THE DEFICIENCY OF CERTAIN ESSENTIAL ELEMENTS ON THE GROWTH OF TOBACCO PLANTS IN SOLUTION CULTURES

BY

J. E. McMURTREY, JR.
Associate Physiologist
Division of Tobacco and Plant Nutrition
Bureau of Plant Industry

UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - Price 5 cents

TECHNICAL BULLETIN No. 340 FEBRUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

DISTINCTIVE EFFECTS OF THE DEFICIENCY OF CERTAIN ESSENTIAL ELEMENTS ON THE GROWTH OF TOBACCO PLANTS IN SOLUTION CULTURES[1]

By J. E. McMURTREY, Jr.

Associate Physiologist, Division of Tobacco and Plant Nutrition, Bureau of Plant Industry[2]

CONTENTS

	Page
Introduction	1
Review of literature	2
Methods of experimentation	4
Experimental data	8
Interpretation and discussion of results	15
Growth in control solutions	16
Nitrogen deficiency	16
Phosphorus deficiency	20
Potassium deficiency	22
Magnesium deficiency	23
Calcium deficiency	25
Interpretation and discussion of results—Continued.	
Boron deficiency	27
Sulphur deficiency	29
Iron deficiency	31
Manganese deficiency	32
Chlorine deficiency	34
Comparison of deficiency effects	34
General considerations	40
Summary	40
Literature cited	42

INTRODUCTION

It is of considerable practical, as well as theoretical, importance to be able to recognize the type of growth produced by plants when the medium in which they are growing is deficient in one of the elements essential to normal development. Reduced growth as expressed in total dry matter produced is a measure of development obtained, but the accompanying growth manifestations are of great importance as a means of recognizing the underlying cause of the condition, thus making possible the correction of the trouble when seen under other similar conditions. The literature is well supplied with quantitative data as to the final weights produced when the medium in which plants are allowed to develop is lacking or deficient in an essential element. There is rarely a case, however, where the author has attempted to discuss the gross morphology of the plants in question in the particular experiment. It is also the usual thing to limit the investigation to a single element. In a few cases detailed anatomical studies of such plants have been made which have contributed much to our knowledge of the subject.

[1] The subject matter of this bulletin, with some rearrangement, is essentially the same as a dissertation submitted to the faculty of the graduate school of the University of Maryland in partial fulfillment of the requirements for the degree of doctor of philosophy.

[2] The writer is indebted to E. S. Johnston, formerly of the University of Maryland, for many valuable suggestions.

There is possibly no plant better suited to a study of this kind than the tobacco, since it is unusually responsive to all changes in environment. Its large leaf surface affords an excellent opportunity for the appearance of marked manifestations of deficiency or hunger symptoms, making easier their distinction. If the wheat plant, for instance, were used, many changes would pass unnoticed which are perfectly evident in a study of the tobacco plant. The tobacco plant will magnify the deficiency manifestations to such an extent that they can be observed with the naked eye in their proper relation. Once the distinctive symptoms of a deficiency of each element are known for one plant species, such as the tobacco plant, their recognition in other plants will be relatively simple. Although there may be minor variations in the symptoms shown by different plant species, the characteristic effects are likely to be essentially the same.

The elements that have been studied are nitrogen, phosphorus, potassium, magnesium, calcium, boron, sulphur, manganese, iron, and chlorine. All these elements, with the possible exception of chlorine, are now generally admitted to be essential to the growth of all the higher plants. The tobacco plant when allowed to develop in a medium in which any one of these elements is deficient, again excepting chlorine, displays a characteristic growth and is smaller. There are certain similarities between the nutritional-deficiency effects produced by the lack of different elements, and there are certain features which serve to distinguish them. A reduction in growth is characteristic where any one element is deficient. Dry weights alone, therefore, fail to give a true picture of the situation. If an element is essential to growth, normal growth is impossible in its absence, but actually complete absence is rarely attained. The seed contains small quantities of essential nutrients, and if the plants are grown for a time in the presence of all elements, the tendency is to set up a reserve of those elements that are readily mobile. Also, even the purest chemicals readily obtainable carry small amounts of various elements as impurities. Any experiment of this kind, therefore, must of necessity resolve itself into a study of the growth of the plant under conditions where the element under consideration is more or less deficient but not entirely lacking. Solution cultures were used in this study. This method is almost ideal for such studies since the elements can be added or withheld at will and the entire root system of the plant can be transferred bodily at any time in its life cycle to the desired solution. This is not possible where solid media are used.

REVIEW OF LITERATURE

It is the intention in this bulletin not to attempt a complete review of the literature touching upon this subject but rather to refer to only a few of the outstanding contributions. Gris (*7*),[3] in his studies on iron chlorosis of plants (1847), was possibly the first to describe a deficiency effect on plants and to give its remedy. Salm-Horstmar (*13*, *14*) was one of the pioneers (1849, 1851) in this type of study. He used the oat plant which was grown in different solid media, particularly charcoal derived from pure sugar and sand, to which certain chemicals were added so as to omit or include the essential elements as desired. This author gives a brief description of the oat plant

[3] Italic numbers in parentheses refer to Literature Cited, p. 42.

growing in media from which the different essential elements were withheld. Mazé (*9*, *10*), in 1914 and 1919, published the results of his studies with maize grown in water cultures. He did not attempt to describe in detail the symptoms produced when the medium was deficient in an essential element.

In 1925 Ginsburg (*6*) gave the results of his studies on the soybean plant. He reported more or less distinct growth effects for the several ions which he considered. The solutions used in this work did not contain the same parts per million of the ions under investigation, and in some cases foreign ions were introduced. In a paper published in 1925 Gericke (*5*) reports stimulation of growth in wheat plants when some of the ions were removed for a period during growth. While details as to the amount of salts used in preparing the nutrient solutions employed in this work are only briefly stated, apparently this investigator increased one of the ions already present in the solution when another was omitted. In the solution from which phosphorus was omitted, for example, where the greatest stimulation is reported, the nitrate ion was increased. It would appear that the plants might have been stimulated in growth by the presence of more nitrate and that they were able to develop for the time under consideration without showing the effects of phosphorus deficiency.

If there is such a thing as stimulation caused by a temporary deficiency, as reported by Gericke (*5*), certain points must be considered. Among these are the season of the year when the experiments are conducted, and the concentration of the ions in the solutions in question. If earlier stages of the experiments are conducted at a season when light conditions are poor, the plants growing in the control solution go through their cycle under these unfavorable conditions. The plants in the solutions lacking a particular ion are delayed in completing their cycle until they are transferred to a complete solution when more favorable light conditions have developed, and stimulation may result in them but not in plants in the control solution for the entire period. On the other hand, the concentration of a given ion may be unfavorable for growth, or the total concentration or the reaction of the solution may be unfavorable, and the condition may be partially corrected by removing the ion in question, which would account for the observed stimulation. In the instance given above, where the nitrate ion is substituted for the phosphate ion in a solution low in nitrate, a temporary stimulation would necessarily result since, as shown later in this bulletin, it is difficult to produce phosphorous deficiency in late stages of growth if the plant is supplied with this ion during its early growth phases. In the light of these considerations it is doubtful whether any of these effects can be considered as true stimulation in growth, the increased growth being due merely to special factors which would hardly operate where proper control of conditions is exercised. Where these factors have been eliminated or properly evaluated, as reported in this bulletin, no consistent stimulation has been found. Russell (*12*), in a recent edition of his monograph, Soil Condition and Plant Growth, brings up to date the contributions on this subject.

Studies on the nutritional-deficiency effects manifested by the tobacco plant have not been extensive, and very few attempts have been made to compare these effects. Wilfarth and Wimmer (*16*), in 1902, reported the effect on the growth of this and other plants when potas-

sium was lacking. Garner and others (*4*), in 1922, described the symptoms of magnesium deficiency on tobacco and corn. This author and his associates (*1*) have described and illustrated magnesium deficiency on tobacco. Moss and others (*11*), in 1927, presented the results of field studies when certain essential elements were absent from the fertilizer mixture. Valleau and Johnson (*15*) report that frenching of tobacco is due to nitrogen deficiency, but, as will be discussed later in this bulletin under effects of nitrogen deficiency, this trouble has not been observed under conditions of extreme nitrogen shortage. McMurtrey (*8*), in 1929, described the effects of boron deficiency on tobacco and demonstrated the improvement in growth obtained when tobacco is grown in an aerated as contrasted with an unaerated nutrient solution. Garner and others (*2*), in 1930, described and illustrated the effects of calcium deficiency on the growth of tobacco. In a paper published the same year, the same authors (*3*) discussed the effect of chlorine on the growth of the tobacco plant.

METHODS OF EXPERIMENTATION

The solutions used in these studies were made up on the basis of a complete solution which was so prepared as to contain the approximate proportions of elements which an average of a large number of chemical analyses of the tobacco plant shows, as mentioned in a previous paper (*8*). In these studies ammonium chloride was added to the control solution used, which increased the nitrogen content slightly and added chlorine to the solution used in the previous study. Table 1 shows the volume molecular concentration of chemically pure salts used in preparing the stock solutions. These stock solutions were diluted 20 times with distilled water for growing the plants. The distilled water used was obtained from a tin-lined still and stored in 5-gallon glass bottles until used. The complete or control solution when diluted contained the following elements expressed in round numbers as parts per million: Nitrogen (N), 225; phosphorus (P), 65; potassium (K), 125; calcium (Ca), 245; magnesium (Mg), 30; sulphur (S), 20; and chlorine (Cl), 50. Boron (B), 0.5, and manganese (Mn), 1.0 parts per million were added to this solution in the form of boric acid (H_3BO_3) and manganese acetate ($Mn(C_2H_3O_2)_2$), respectively, as chemically pure salts. Iron, usually in the form of iron citrate (United States Pharmacopoeia), was added daily to all cultures during the first few weeks and every other day during the last few weeks at the rate of 1 cc of a 0.5 per cent solution per liter of culture solution. The form of iron salt used was different in the cultures from which it was desired to withhold manganese. Ferrous sulphate free from this element was substituted for the citrate in this case. For other ions, the solutions that did not carry one of the ions contained the same parts per million as given for the complete solution with only slight variations.

TABLE 1.—*Volume-molecular concentrations of chemically pure salts used in preparing stock solutions*

Solutions containing—	Solution designation	Chemically pure salts												
		$Ca(NO_3)_2$	$CaH_4(PO_4)_2$	$CaCl_2$	$CaCO_3$	KNO_3	KH_2PO_4	K_2HPO_4	$Mg(NO_3)_2$	$MgSO_4$	$MgCl_2$	NH_4NO_3	$(NH_4)_2SO_4$	NH_4Cl
All elements	C[1]	0.1235				0.0217	0.0422		0.0124	0.0125				0.0280
Do	C[2]		0.0052		0.1180			0.0320		.0125	0.0140	0.1600		
No added nitrogen	N		.0052		.1180			.0320		.0125	.0140			
No added phosphorus	P	.1026		0.0141		.0637			.0124	.0125		.0140		
No added potassium	K	.1044	.0211						.0124	.0125		.0208		.0280
No added calcium	Ca					.0217	.0422		.0124	.0125		.1242		.0280
No added magnesium	Mg	.1235				.0217	.0422						0.0125	.0280
No added sulphur	S	.1235				.0217	.0422		.0124		.0140	.0140		
No added chlorine	Cl	.1235				.0217	.0422		.0124	.0125		.0140		
No added boron	B	.1235				.0217	.0422		.0124	.0125				.0280
No added manganese	Mn	.1235				.0217	.0422		.0124	.0125				.0280
No added iron	Fe	.1235				.0217	.0422		.0124	.0125				.0280

It is to be seen from Table 1 that in order to supply the same quantity of nitrogen it was necessary to substitute some ammonia nitrogen for nitrate nitrogen in certain solutions. Although this method of maintaining a constant supply of elements may be open to objection, it was considered more satisfactory than introducing a foreign ion or increasing ions already present, as Ginsburg has done (*6*), or only increasing ions already present, as Gericke (*5*) did. The solution to which no nitrogen was added is open to the objection that it was supplied with calcium as the carbonate, but in order to determine whether this solution would give satisfactory growth with the addition of nitrogen a second control (C^2) was introduced in series 3 with the nitrogen supplied as ammonium nitrate. This control also serves to throw light on whether ammonium nitrate as used in the solution deficient in calcium will produce satisfactory growth with calcium supplied in this form, as well as in the other cases where the ammonia form of nitrogen is substituted for the nitrate form. When properly prepared, the stock solutions of the volume molecular concentration given in the table show little or no precipitate, with the exception of the solutions containing calcium carbonate. A necessary precaution is that calcium nitrate be dissolved separately and not added to the other dissolved salts until most of the volume of water has been added. However, as will be shown later, the heavy precipitate produced by the addition of calcium carbonate does not materially affect the ability of the solution to produce satisfactory growth when all elements are present.

The reaction of these solutions when freshly prepared, as determined by use of the quinhydrone electrode, varied from about pH 4.0 to 8.0. The pH values of the solutions designated C^1, S, Fe, B, Mn, Mg, and K ranged from 4.0 and 4.5. The pH values of the solutions to which no chlorine and no calcium were added ranged from 4.6 and 5.0. The freshly prepared solution containing no added phosphorus had a pH of about 6.0, whereas the solutions designated as C^2 and N had pH values ranging from pH 7.6 and 8.0. The control solutions C^1 and C^2 therefore showed approximately the two extreme pH values. Since growth in these two solutions was normal, it would appear that the reaction range of these solutions was satisfactory for growth of the tobacco plant, so that the observed effects on growth may be attributed to a deficiency of the ions in question and not to the reaction of the solution.

In preliminary trials in which the weights of plants were not obtained, the above solutions, which will be referred to as standard solutions, were compared with solutions made up of three salt combinations, 0.005 volume molecular concentration, as suggested by Gericke (*5*). Boron, manganese, and iron were supplied as in the standard series, the three salt-control solutions being used in observing effects when these elements were omitted. In series 2 a comparison was made between the standard group of solutions and a group of solutions devised by Johnston[4] in which the salts used and the parts per million of essential elements varied to some extent from the standard solutions, and none of these solutions contained chlorine save the complete (C^3). These solutions also produced the typical growth effects that will be discussed later.

[4] The solutions referred to were devised by Earl S. Johnston, formerly of the University of Maryland, for use in deficiency studies with the tomato plant.

The containers used for growing the plants were commercial 2-quart glass fruit jars, except those for the plants from which manganese was withheld. In this case 2-liter pyrex beakers were substituted. This change was made because it was found in preliminary trials that omitting manganese produced no effects where fruit jars were used as containers. The plants were held in position by paraffined cork stoppers or by paraffined boards with suitable holes, placed on the beakers. It was necessary to stake the plants to hold them upright. Both beakers and jars were wrapped with two thicknesses of heavy wrapping paper to exclude most of the light and prevent the growth of algae in the solution. In all cases where yields are reported the cultures were aerated by bubbling with compressed air. The rate during the first four weeks of growth was approximately 1 liter of air per hour, but it was found necessary to double this rate during the last few weeks of growth. If for any reason the bubbling was discontinued during the last week or so of growth the roots at once began to die, with the result that the leaves wilted and many of the lower leaves dried out. Such plants did not die but were markedly stunted in growth.

In some cases the solutions were renewed, whereas in others there were no renewals. The cultures were made up to the original volume by adding distilled water every few days during the early stages of growth and every second or third day during the later stages. The volume of water necessary in each case was recorded. Leaf counts and measurements of the tops (height) and roots (length) were made at suitable intervals, and recorded. It was found difficult to measure the roots accurately during the later stages of growth because they became so tangled and matted.

The Connecticut Broadleaf variety of tobacco was used in these studies. The seeds were sown in a flat of steam-sterilized greenhouse potting soil, and after one month the seedlings were set in thumb pots containing the same soil sterilized in the same manner. After the plants had been allowed to develop in these pots for a time, usually one month, the roots were washed free of the soil, and the plants transferred to the various solutions. Although every effort was made to have the plants free from harmful organisms it was found that in some cases these were present and to some extent interfered with the growth of the plants.

In order to overcome this difficulty several disinfectants were tried and a silver nitrate solution, 1:1,000, was found to be the most satisfactory. The roots were immersed in this solution for 5 minutes, then the whole plant was immersed for another 5 minutes, thus giving the roots a 10-minute treatment and the tops a 5-minute treatment. Plants treated in this manner were slow in starting growth after being placed in water cultures and especially was this so in the solutions containing no added chlorine. However, such plants eventually outgrew the untreated plants and were relatively free from organisms. Only plants of the third series were treated in this manner.

The temperature and humidity conditions in the greenhouse in which these studies were conducted showed the usual daily fluctuations. The attempt was made to hold the night temperatures between 65° and 70° F. and the day temperatures between 75° and 80°.

EXPERIMENTAL DATA

Data are presented for three series of experiments conducted during the season 1929–30, but this work was based on preliminary studies covering a period of several years. One phase of the work has been reported in a previous paper (*8*). During the season of 1928–29 observations were made on cultures grown in the standard series of solutions with and without aeration. The symptoms manifested by plants growing under these two conditions were essentially the same although the plants growing in the unaerated solutions were later in manifesting the characteristic symptoms due to the deficiency of the different elements because of slower growth. The plants were much smaller and their roots were such that it was almost impossible to observe any difference between those from the various solutions, with the exception of those grown without added phosphorus in the unaerated cultures. In those the roots were unusually long for roots grown in an unaerated solution, and in fact they were almost as long as those developed by plants in the same solution aerated.

The standard series of solutions were also compared with the three salt solutions used by Gericke (*5*). These comparisons were made in both aerated and unaerated solutions, and the above observations again were applicable. The symptoms produced again were practically identical with those of the standard series of solutions where the plants were transferred to the solutions lacking the different elements and allowed to grow for the period of the observations.

It appears, therefore, that the effects produced in solutions which are aerated or unaerated are essentially the same. Also that solutions made up of different salt combinations that lack the same element produce much the same effects on growth when plants are allowed to develop in them for a considerable period.

The three points taken up in the data presented are: Series 1, the effect of the removal of the various ions at different periods during the growth of the tobacco plant; series 2, a comparison of the effects on growth of two solutions each lacking the same ion but made up of different salts supplying the essential elements at different rates; and series 3, the effect on recovery when the different essential elements are supplied after having been withheld for certain periods.

In order to determine the dry weight at the beginning of the experiment a sample of 10 plants was taken from the general lot used in each series. The average air-dry weight per plant in grams for 10 sample plants taken from each lot used was: Series 1, 0.54; series 2, 0.25; and series 3, 0.33. The curves given for series 1 have for their starting point 14.9 cm as an average for 10 sample plants for height of tops, and 9.2 cm for length of roots. This explains why some of these curves show a downward trend for plants measured November 9, since some plants were below average.

The data presented in Table 2 for series 1 show the average measurements and leaf counts for duplicate cultures at different intervals where the plants were transferred at approximately weekly intervals from a solution containing all the essential elements and designated as the control solution (C^1), to the solutions lacking one of them. This table also shows average measurements and leaf counts for duplicate cultures, which were allowed to grow in the solutions lacking each of the essential elements, which were not changed, as compared with the measurements and leaf counts of plants in the control solution, where all were supplied.

TABLE 2.—*Average measurements and leaf counts at intervals on tobacco plants grown in nutrient solutions with and without the removal of the different essential elements at intervals during growth for the period November 1, 1929, to January 2, 1930 (series 1)*

Elements omitted and date plants were transferred to solution indicated from control (C¹) [1]	Length of roots (centimeters)						Height of tops (centimeters)								Number of leaves					
	Nov. 9	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Jan. 2	Nov. 9	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Dec. 13	Dec. 26	Jan. 2	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Dec. 13	Jan. 2
Nitrogen:																				
Nov. 1	14.0	37.5	42.5	49.0	54.5	60.0	10.5	10.5	11.5	12.5	13.5	16.0	19.0	23.0	5.5	7.5	7.5	8.5	10.5	15.0
Nov. 9	14.0	37.5	51.5	57.0	65.0	75.0	7.0	11.0	12.5	15.0	16.0	20.5	26.5	33.0	7.0	8.5	9.5	10.5	11.0	16.0
Nov. 15	16.5	31.0	33.0	41.5	36.5	50.0	7.0	10.5	17.5	23.0	26.5	31.5	52.5	61.5	7.5	10.5	11.5	12.5	14.0	21.0
Nov. 22	14.5	36.5	51.0	53.0	44.5	59.0	9.0	13.5	21.5	35.5	46.0	72.0	89.0	90.0	8.0	11.0	13.0	14.0	20.5	21.0
Nov. 29	16.0	35.5	39.5	50.5	51.5	55.0	6.0	10.0	21.0	32.0	42.5	67.0	92.0	95.0	8.0	11.5	13.5	15.5	20.0	23.0
Phosphorus:																				
Nov. 1	16.0	37.5	49.0	68.0	75.0	60.0	11.0	12.0	14.0	14.5	18.0	20.0	24.5	29.0	7.0	8.5	9.5	10.0	10.0	15.0
Nov. 9	13.0	32.5	45.0	56.5	42.5	57.5	7.0	11.5	17.0	22.0	27.5	39.0	58.0	69.0	7.5	9.5	11.0	12.0	13.5	13.5
Nov. 15	12.5	26.0	32.5	30.5	33.5	42.5	8.5	12.0	18.5	25.0	32.0	50.5	81.0	93.5	8.0	11.5	12.5	14.0	15.5	22.5
Nov. 22	13.5	32.5	32.5	33.0	31.5	32.5	10.0	13.0	19.0	28.0	38.5	60.5	88.0	92.0	8.0	11.5	13.0	15.0	16.5	20.0
Nov. 29	12.0	32.0	32.0	33.0	34.0	31.5	7.0	10.5	20.5	30.0	40.0	65.0	103.5	106.0	8.0	12.0	14.0	16.0	18.5	23.0
Potassium:																				
Nov. 1	13.0	31.5	43.5	41.5	38.5	37.5	11.5	14.0	19.5	25.0	32.5	49.5	69.5	83.5	8.0	10.0	12.0	14.0	17.0	23.5
Nov. 9	11.5	28.0	41.5	51.5	40.0	36.5	9.0	12.0	18.0	25.0	33.0	46.5	62.0	74.0	7.5	10.5	12.0	13.5	16.5	22.5
Nov. 15	13.5	30.5	44.0	37.5	35.5	39.0	11.0	15.0	23.5	35.5	50.0	78.5	99.0	101.0	8.0	10.5	12.5	14.5	18.5	22.5
Nov. 22	15.0	28.5	41.0	43.5	37.0	44.0	10.5	14.5	24.0	36.0	53.0	88.0	110.0	111.0	8.0	11.5	13.5	15.5	19.5	21.5
Nov. 29	13.0	25.0	33.5	34.5	33.0	35.0	8.5	13.5	21.0	29.5	41.0	64.0	79.0	81.0	8.5	11.5	13.0	14.5	16.5	19.5
Calcium:																				
Nov. 1	14.0	18.5	24.0	26.5	27.0	24.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	6.5	6.5	6.5	6.5	6.5	7.5
Nov. 9	13.5	18.5	23.5	25.5	26.0	32.5	10.0	12.0	12.0	12.0	13.0	13.5	13.0	13.0	7.5	8.0	8.0	8.0	8.0	8.5
Nov. 15	13.5	30.5	36.5	38.5	32.5	37.5	9.5	14.0	22.0	26.5	32.0	34.0	35.0	35.0	7.5	10.5	11.0	12.0	12.0	11.5
Nov. 22	12.5	23.0	26.0	26.5	28.5	33.5	9.5	13.5	18.5	24.0	31.0	42.5	54.0	57.5	7.5	10.0	12.0	14.0	16.0	18.5
Nov. 29	13.5	33.0	45.0	45.0	46.5	42.5	9.5	13.0	23.5	40.0	56.0	91.0	104.0	105.0	8.0	11.0	13.0	16.0	19.0	21.0
Magnesium:																				
Nov. 1	13.0	30.0	38.0	43.5	35.0	32.5	9.0	11.0	13.0	14.5	16.0	17.5	20.5	21.0	7.5	9.5	10.5	12.0	13.5	18.0
Nov. 9	12.5	28.0	41.5	46.5	45.0	42.5	9.5	14.5	23.0	28.0	33.5	46.5	53.0	55.5	8.0	11.0	13.0	14.0	17.0	19.5
Nov. 15	16.0	22.0	30.0	30.0	31.5	38.5	10.0	13.0	19.0	27.0	36.0	48.0	63.5	67.5	8.0	10.5	12.5	14.0	17.0	20.5
Nov. 22	13.5	32.0	39.5	37.5	39.0	35.0	9.5	13.5	23.0	33.5	49.0	74.0	93.5	98.5	8.5	11.5	13.5	15.5	18.5	21.5
Nov. 29	15.0	36.0	30.0	35.5	36.5	34.5	9.0	14.0	18.5	27.5	37.5	64.0	94.0	97.5	9.0	10.5	12.5	15.0	18.0	21.5
None (C¹):																				
Nov. 1	14.5	26.0	36.5	37.0	37.0	37.5	11.0	15.5	23.5	34.0	45.0	71.0	95.0	105.0	8.0	11.0	12.5	14.5	17.5	23.0
Nov. 9	14.5	30.5	42.0	45.5	46.5	48.5	11.0	15.5	25.0	38.5	51.5	81.5	105.0	106.0	8.0	12.0	13.0	15.5	18.5	23.0
Nov. 15	15.0	31.0	41.5	44.5	47.5	45.0	8.5	13.0	22.5	38.5	56.0	86.5	104.5	105.0	8.5	11.5	13.5	15.5	19.0	22.5
Nov. 22	16.0	32.5	41.5	44.0	35.0	37.0	8.5	12.5	23.0	37.5	61.5	96.0	107.5	110.0	8.0	11.0	14.0	16.0	19.0	20.0
Nov. 29	13.0	30.5	43.5	42.0	37.5	32.5	6.5	11.5	20.0	33.5	45.5	74.0	101.5	102.5	8.0	11.0	12.5	14.5	17.5	22.0

[1] Solutions for Nov. 1 group remained unchanged for period of experiment.

TABLE 2.—*Average measurements and leaf counts at intervals on tobacco plants grown in nutrient solutions with and without the removal of the different essential elements at intervals during growth for the period November 1, 1929, to January 2, 1930 (series 1)*—Continued

Elements omitted and date plants were transferred to solution indicated from control (C^1)	Length of roots (centimeters)						Height of tops (centimeters)								Number of leaves					
	Nov. 9	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Jan. 2	Nov. 9	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Dec. 13	Dec. 26	Jan. 2	Nov. 16	Nov. 23	Nov. 30	Dec. 6	Dec. 13	Jan. 2
Boron:																				
Nov. 1	14.0	15.0	15.5	17.0	17.0	19.5	8.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	8.0	8.0	8.0	8.0	8.0	8.5
Nov. 9	12.5	24.5	25.0	25.0	25.0	25.0	12.0	15.0	17.0	17.5	17.5	17.5	17.5	17.5	8.0	9.5	10.0	10.0	10.0	10.5
Nov. 15	20.0	29.0	33.0	33.5	33.0	35.5	10.0	14.5	23.0	27.0	27.0	27.0	27.0	27.0	9.0	12.0	13.0	13.0	13.0	14.5
Nov. 22	13.5	30.5	43.0	49.5	47.5	44.0	10.0	14.0	22.5	29.0	31.5	33.0	32.5	32.5	7.5	10.5	12.5	13.0	14.0	15.5
Nov. 29	13.5	31.0	42.5	50.0	41.0	30.5	9.0	14.0	24.0	36.0	48.0	62.5	66.0	67.0	8.0	11.0	12.5	14.5	16.5	18.5
Sulphur:																				
Nov. 1	12.0	31.5	43.0	46.5	43.0	35.5	11.0	14.5	20.0	25.5	30.5	45.5	57.5	60.0	8.5	11.0	11.5	12.5	14.5	16.5
Nov. 9	15.0	27.0	35.0	47.0	47.5	39.0	11.0	15.0	23.0	34.0	44.0	60.0	62.5	64.0	8.0	11.0	12.5	14.0	16.0	17.5
Nov. 15	12.5	29.5	42.5	45.0	41.0	36.5	10.5	14.5	22.5	34.5	44.5	60.5	67.0	74.0	8.0	11.5	13.5	15.0	16.5	20.0
Nov. 22	15.0	29.5	45.0	40.5	40.5	41.0	10.0	15.0	25.0	41.0	61.5	89.0	98.0	99.5	8.0	11.5	13.5	16.0	18.5	20.5
Nov. 29	11.5	30.0	38.0	41.5	45.0	40.0	8.0	12.5	22.5	36.5	48.0	69.0	82.5	83.5	7.5	10.5	13.0	14.0	17.0	20.5
Manganese:																				
Nov. 1	16.0	25.5	32.0	32.5	32.5	35.5	9.5	13.5	21.5	33.5	45.0	65.0	81.5	83.5	8.0	11.5	13.5	14.5	17.5	20.0
Nov. 9	13.5	21.5	26.0	27.0	27.5	30.0	9.0	12.5	17.0	25.5	34.0	50.5	73.0	85.0	7.5	10.5	12.5	14.0	17.0	22.5
Nov. 15	12.0	18.5	29.5	33.5	34.5	39.0	7.5	11.5	15.0	26.0	38.0	65.5	102.5	106.5	7.0	11.0	13.0	15.0	18.0	21.0
Nov. 22	13.0	29.5	43.0	47.5	47.5	55.0	7.0	10.5	17.5	31.5	50.0	85.0	123.5	125.0	8.0	12.0	14.0	16.0	19.0	22.5
Nov. 29	14.0	28.0	34.0	40.0	40.0	35.0	7.0	10.5	17.5	27.5	39.5	67.0	103.5	111.0	7.0	10.0	12.0	14.0	17.5	23.0
Iron:																				
Nov. 1	12.0	25.5	31.0	31.5	32.0	32.0	9.0	11.5	17.0	22.0	27.0	35.0	41.5	44.5	8.0	11.0	12.0	14.5	16.0	21.0
Nov. 9	14.0	30.0	31.0	27.5	29.5	29.5	10.5	15.0	20.0	27.5	34.5	55.0	76.0	85.0	7.5	11.5	12.0	14.0	17.0	23.0
Nov. 15	13.0	27.0	37.0	32.5	35.0	35.5	11.0	15.5	22.5	34.5	51.0	82.0	103.5	106.5	8.0	11.0	13.5	15.5	18.5	23.0
Nov. 22	11.0	25.5	36.5	35.5	36.5	34.0	8.0	12.0	18.0	27.5	38.5	57.5	78.5	84.0	7.5	10.5	12.5	14.5	17.0	22.0
Nov. 29	14.0	29.0	48.5	56.0	44.5	49.5	10.0	14.0	22.5	37.0	50.0	81.0	107.5	112.5	8.0	11.0	13.0	15.0	18.5	21.5
Chlorine:																				
Nov. 1	14.0	33.0	51.0	54.5	54.5	59.0	9.0	13.0	22.5	36.5	51.0	82.0	101.0	101.0	7.5	10.5	13.0	15.0	17.5	21.0
Nov. 9	17.0	30.5	34.0	35.0	37.0	37.5	9.0	12.5	21.0	32.5	47.5	76.0	99.5	100.5	8.5	12.0	14.0	15.5	18.5	21.5
Nov. 15	15.0	30.5	40.5	42.5	42.5	40.0	8.5	12.5	22.0	35.5	49.0	79.0	98.5	101.0	9.0	12.0	14.0	16.0	19.5	22.0
Nov. 22	15.0	33.0	34.5	32.5	32.5	32.5	9.0	14.0	21.5	30.0	46.5	80.0	110.0	110.0	8.5	11.5	13.5	15.0	18.0	21.0
Nov. 29	13.5	30.0	35.0	35.0	35.0	32.5	6.5	10.5	17.5	28.0	41.0	73.0	103.5	106.5	8.0	10.5	12.5	14.5	18.0	21.0

The data presented in Table 3 show the average air-dry weights of plants from the same series. The total quantity of water used during the entire period and the amount of water for each gram of air-dry weight also are shown. This table also shows the percentages of root, stalk, and leaf, based on the air-dry weights.

TABLE 3.—*Average air-dry weight, volume of water used, and percentage of leaf, stalk, and root for tobacco plants grown in nutrient solutions with and without the removal of the different essential elements at intervals during growth for the period November 1, 1929, to January 2, 1930 (series 1)*

Elements omitted and date plants were transferred into solution indicated from control (C[1])	Air-dry weight (grams)				Water used (cubic centimeters)		Percentages based on air-dry weight		
	Leaf	Stalk	Root	Total	Total for period	Quantity per gram, air-dry weight	Leaf	Stalk	Root
Nitrogen:									
Nov. 1	1.13	0.40	0.35	1.88	910	484	60.1	21.3	18.6
Nov. 9	1.60	.85	.65	3.10	1,608	519	51.6	27.4	21.0
Nov. 15	2.33	1.55	.80	4.68	2,350	502	49.8	33.1	17.1
Nov. 22	4.48	4.43	1.08	9.99	5,280	529	44.8	44.4	10.8
Nov. 29	5.35	5.58	2.03	12.96	6,518	503	41.3	43.1	15.6
Phosphorus:									
Nov. 1	2.35	.88	.85	4.08	1,840	451	57.6	21.6	20.8
Nov. 9	4.10	2.30	1.13	7.53	3,335	443	54.4	30.6	15.0
Nov. 15	6.15	3.98	1.63	11.76	4,683	398	52.3	33.8	13.9
Nov. 22	6.40	5.00	1.65	13.05	5,758	441	49.0	38.3	12.7
Nov. 29	8.50	7.15	2.25	17.90	6,810	380	47.5	39.9	12.6
Potassium:									
Nov. 1	6.13	3.15	1.25	10.53	4,993	474	58.2	29.9	11.9
Nov. 9	5.33	2.98	1.05	9.36	4,770	510	57.0	31.8	11.2
Nov. 15	6.40	5.80	1.48	13.68	6,418	469	46.8	42.4	10.8
Nov. 22	8.05	7.30	1.98	17.33	7,693	444	46.5	42.1	11.4
Nov. 29	5.30	4.60	1.63	11.53	4,763	413	46.0	39.9	14.1
Calcium:									
Nov. 1	2.48	.80	.45	3.73	1,723	462	66.5	21.5	12.0
Nov. 9	3.70	1.80	.95	6.45	3,180	493	57.4	27.9	14.7
Nov. 15	5.55	2.93	1.25	9.73	4,683	481	57.0	30.1	12.9
Nov. 22	5.70	4.08	1.80	11.58	4,523	391	49.2	35.2	15.6
Nov. 29	7.85	7.03	2.43	17.31	7,143	413	45.4	40.6	14.6
Magnesium:									
Nov. 1	4.08	.45	.53	5.06	2,780	549	80.6	8.9	10.5
Nov. 9	6.33	1.83	.83	8.99	4,780	532	70.4	20.4	9.2
Nov. 15	6.83	2.50	1.20	10.53	5,333	506	64.9	23.7	11.4
Nov. 22	7.43	6.25	1.75	15.43	6,785	440	48.1	40.5	11.4
Nov. 29	7.18	5.80	1.98	14.96	7,103	475	48.0	38.8	13.2
None (C[1]):									
Nov. 1	6.23	5.55	1.53	13.31	5,125	385	46.8	41.7	11.5
Nov. 9	6.60	5.80	1.70	14.10	6,678	474	46.8	41.1	12.1
Nov. 15	7.05	7.13	1.63	15.81	6,873	435	44.6	45.1	10.3
Nov. 22	6.98	8.33	1.98	17.29	7,428	430	40.4	48.2	11.4
Nov. 29	7.85	7.00	2.35	17.20	6,235	363	45.6	40.7	13.7
Boron:									
Nov. 1	4.50	.55	.93	5.98	2,190	366	75.3	9.2	15.5
Nov. 9	4.65	1.05	.80	6.50	2,695	415	71.5	16.2	12.3
Nov. 15	6.60	2.05	1.18	9.83	3,786	385	67.1	20.9	12.0
Nov. 22	6.60	2.43	1.25	10.28	3,945	384	64.2	23.6	12.2
Nov. 29	5.10	3.90	1.38	10.38	4,088	394	49.1	37.6	13.3
Sulphur:									
Nov. 1	3.70	2.73	1.25	7.68	2,963	386	48.2	35.5	16.3
Nov. 9	3.68	3.65	1.05	8.38	3,408	407	43.9	43.6	12.5
Nov. 15	4.28	4.10	1.30	9.68	4,048	418	44.2	42.4	13.4
Nov. 22	7.60	8.33	1.90	17.83	6,798	381	42.6	46.7	10.7
Nov. 29	5.35	5.15	1.20	11.70	4,055	347	45.7	44.0	10.3
Manganese:									
Nov. 1	5.78	3.73	1.38	10.89	6,050	556	53.1	34.3	12.6
Nov. 9	5.65	3.68	1.35	10.68	4,225	396	52.9	34.5	12.6
Nov. 15	7.15	5.90	1.80	14.85	7,480	504	48.2	39.7	12.1
Nov. 22	8.88	8.48	1.90	19.26	9,710	504	46.1	44.0	9.9
Nov. 29	8.13	7.45	2.05	17.63	7,150	406	46.1	42.3	11.6
Iron:									
Nov. 1	3.95	2.20	.80	6.95	3,350	482	56.8	31.7	11.5
Nov. 9	5.40	4.33	1.20	10.93	4,455	408	49.4	39.6	11.0
Nov. 15	7.30	7.53	1.70	16.53	7,615	461	44.2	45.5	10.3
Nov. 22	5.90	4.90	1.30	12.10	5,050	417	48.8	40.5	10.7
Nov. 29	9.25	8.75	2.15	20.15	9,028	448	45.9	43.4	10.7
Chlorine:									
Nov. 1	7.30	6.23	1.95	15.48	7,643	494	47.2	40.2	12.6
Nov. 9	6.03	5.68	1.60	13.31	6,598	496	45.3	42.7	12.0
Nov. 15	7.10	6.53	1.58	15.21	6,775	445	46.7	42.9	10.4
Nov. 22	8.15	7.35	2.10	17.60	7,370	419	46.3	41.8	11.9
Nov. 29	7.65	7.63	2.03	17.31	6,895	398	44.2	44.1	11.7

Table 4 gives length of roots, height of tops, and leaf counts of plants from series 2, which were grown from January 16 to February 28, 1930. The figures in this table are the averages of five plants for each group. The solutions were not changed during this period.

TABLE 4.—*Average measurements and leaf counts at intervals on tobacco plants grown in nutrient solutions with and without the addition of the different essential elements in a comparison of two groups of solutions of varying composition, for the period January 16 to February 28, 1930 (series 2)*

Solutions and elements omitted	Length of roots (centimeters)				Height of tops (centimeters)				Number of leaves			
	Jan. 18	Jan. 29	Feb. 13	Feb. 27	Jan. 18	Jan. 29	Feb. 13	Feb. 27	Jan. 18	Jan. 29	Feb. 13	Feb. 27
Standard group of solutions:												
Nitrogen	12.0	17.8	24.2	30.6	2.8	3.0	3.0	3.4	4.2	5.6	7.2	8.6
Phosphorus	10.6	21.4	34.6	39.4	2.4	2.8	4.8	5.0	4.4	6.0	8.2	9.4
Potassium	12.2	18.4	40.2	36.8	2.8	3.4	6.2	9.2	3.8	6.0	10.4	14.4
Calcium	12.6	10.6	11.0	12.0	3.4	3.8	3.0	3.0	4.2	6.2	6.2	6.2
Magnesium	10.2	17.4	39.4	42.2	2.8	3.4	4.4	4.8	3.6	6.2	10.0	13.4
None (C^1)	9.8	21.6	36.8	35.6	3.0	4.2	19.8	61.2	4.2	7.4	13.0	19.6
Boron	8.2	17.0	25.0	25.4	2.4	2.8	6.2	6.2	4.0	6.6	9.4	9.8
Sulphur	11.8	18.6	29.6	30.0	3.0	3.8	7.0	7.6	3.8	7.0	9.8	10.6
Manganese	10.0	13.2	19.4	24.2	2.2	2.2	3.4	6.6	3.4	5.6	7.8	13.0
Iron	8.8	13.0	22.8	25.0	2.2	2.4	5.8	10.0	3.8	6.6	10.8	14.2
Chlorine	9.0	14.8	36.4	33.6	2.4	2.6	12.6	47.0	3.2	5.6	11.0	17.8
Solutions used for comparison with standard group:												
Nitrogen	10.6	21.6	22.4	30.6	3.0	3.0	3.0	3.2	4.4	6.8	7.2	8.2
Phosphorus	9.6	23.6	34.6	34.2	2.4	3.0	4.8	5.2	4.2	5.8	8.6	9.8
Potassium	10.8	17.2	36.8	36.0	2.6	3.6	6.6	10.4	3.8	6.2	10.6	14.4
Calcium	10.4	10.4	10.4	10.4	3.2	3.2	2.4	2.4	3.8	5.6	5.0	5.4
Magnesium	10.8	18.2	37.6	35.8	2.4	2.8	4.0	5.0	3.0	6.2	10.4	13.4
None (C^2)	10.2	23.6	36.2	34.4	3.2	5.2	21.2	56.8	4.6	8.2	12.4	16.4
Boron	9.6	14.2	20.8	21.0	2.2	3.2	4.4	4.4	3.8	7.0	8.8	9.2
Sulphur	10.6	17.0	32.8	32.0	2.6	3.6	6.6	7.4	4.0	7.0	9.8	11.4
Manganese	10.0	12.8	24.6	32.4	2.4	2.6	6.8	20.6	3.6	6.0	9.2	14.6
Iron	11.4	14.0	19.8	21.8	2.6	3.2	5.4	8.6	3.8	6.8	10.0	12.6
Chlorine	10.4	15.0	30.4	28.8	2.2	2.8	8.6	29.6	3.4	5.8	9.8	15.2

The figures presented in Table 5 give the quantitative data from series 2 consisting of air-dry weights, total quantity of water used, quantity of water used per gram of air-dry weight, as well as percentages of leaf, stalk, and root. It is to be seen from these data that in both groups solutions lacking the same ions have produced practically the same amount of growth, with few exceptions, and the decrease in growth where each element is lacking is in about the same proportion.

TABLE 5.—*Average air-dry weight, volume of water used, and percentage of leaf, stalk, and root for tobacco plants grown in nutrient solutions with and without the addition of the different essential elements in a comparison of two groups of solutions of varying composition, for the period January 16 to February 28, 1930 (series 2)*

Solutions and treatment	Air-dry weight (grams)				Water used (cubic centimeters)		Percentages based on air-dry weight		
	Leaf	Stalk	Root	Total	Total for period	Quantity per gram air-dry weight	Leaf	Stalk	Root
Standard group of solutions:									
No added nitrogen	0.39	0.09	0.09	0.57	328	575	68.4	15.8	15.8
No added phosphorus	.91	.15	.27	1.33	570	429	68.4	11.3	20.3
No added potassium	3.34	.38	.39	4.11	2,200	535	81.3	9.2	9.5
No added calcium	.73	.20	.21	1.14	446	391	64.0	17.6	18.4
No added magnesium	2.66	.09	.16	2.91	1,277	439	91.4	3.1	5.5
Control (C[1])	7.88	6.35	1.78	16.01	5,011	313	49.2	39.7	11.1
No added boron	3.04	.46	.34	3.84	1,170	305	79.2	12.0	8.8
No added sulphur	1.32	.50	.41	2.23	678	304	59.2	22.4	18.4
No added manganese	2.08	.35	.37	2.80	1,661	593	74.3	12.5	13.2
No added iron	2.29	.67	.48	3.44	1,114	324	66.6	19.5	13.9
No added chlorine	7.06	5.06	1.61	13.73	4,222	308	51.4	36.9	11.7
Solutions used for comparison with standard group:									
No added nitrogen	.42	.11	.15	.68	380	559	61.8	16.2	22.0
No added phosphorus	1.07	.20	.28	1.55	658	425	69.0	12.9	18.1
No added potassium	3.39	.40	.44	4.23	2,190	518	80.1	9.5	10.4
No added calcium	.64	.16	.21	1.01	379	375	63.4	15.8	20.8
No added magnesium	2.45	.07	.11	2.63	1,281	487	93.1	2.7	4.2
Control (C[3])	4.23	4.57	1.09	9.89	3,393	343	42.8	46.2	11.0
No added boron	2.74	.34	.25	3.33	1,019	306	82.3	10.2	7.5
No added sulphur	1.42	.40	.48	2.30	737	320	61.7	17.4	20.9
No added manganese	4.04	1.63	.89	6.56	3,355	511	61.6	24.8	13.6
No added iron	1.70	.48	.32	2.50	953	381	68.0	19.2	12.8
No added chlorine	3.46	2.46	.84	6.76	2,263	335	51.2	36.4	12.4

In all cases in which the data from the first two series are not consistent one of the main contributing causes was the fact that parasitic organisms occasionally were accidently introduced on the plant roots. In an attempt to overcome this objectionable feature the plants of series 3 were disinfected with silver nitrate, as previously mentioned.

The data presented in Table 6 give length of roots, height of tops, and leaf counts for plants grown from April 1 to May 28, 1930 (series 3), where a study was made of the effect upon recovery of the plants when each essential element was withheld for a certain period. The measurements and leaf counts were made at times when the plants were changed from one solution to the other. All solutions were changed on the dates indicated.

TABLE 6.—*Average measurements and leaf counts at intervals on tobacco plants grown in nutrient solutions with and without the different essential elements supplied at intervals, showing recovery during the period April 1 to May 28, 1930 (series 3)*

Elements omitted and date plants were transferred to control (C^1) from solution indicated	Length of roots (centimeters)				Height of tops (centimeters)				Number of leaves			
	Apr. 1	May 1	May 14	May 28	Apr. 1	May 1	May 14	May 28	Apr. 1	May 1	May 14	May 28
Nitrogen	11.8	15.5	29.0	41.3	2.0	2.0	3.3	3.3	4.0	6.0	6.5	6.8
May 14	10.0	12.3	22.7	35.0	2.0	2.0	3.0	5.3	4.0	6.3	6.3	9.7
May 1	10.3	10.3	36.0	39.3	2.0	2.0	8.7	46.7	3.3	4.7	9.7	15.7
Phosphorus	11.8	43.8	51.3	54.0	2.3	2.5	3.5	4.3	4.0	6.8	8.0	8.5
May 14	12.0	45.3	60.3	60.3	2.0	2.3	3.3	8.0	3.3	6.7	7.0	10.3
May 1	10.0	40.0	48.0	50.7	2.3	3.3	22.0	75.0	3.7	7.7	13.0	19.3
Potassium	8.5	42.0	39.5	38.3	2.0	5.8	10.8	14.5	3.8	10.3	13.3	15.3
May 14	11.0	40.3	36.0	39.7	2.0	6.7	12.0	27.3	4.3	10.7	13.3	18.0
May 1	9.3	38.3	36.3	37.3	2.0	5.0	26.7	81.7	4.3	10.0	14.7	20.3
Calcium	11.5	12.8	17.3	20.5	2.3	2.3	2.0	2.0	4.3	4.3	4.3	4.3
May 14	12.7	15.0	17.3	17.3	2.0	2.0	2.0	2.0	4.7	4.3	4.3	4.3
May 1	10.0	17.0	42.0	46.0	2.3	2.0	12.0	47.7	4.0	4.0	9.0	15.0
Magnesium	12.0	46.8	43.8	46.3	2.3	5.8	8.5	10.3	4.0	11.8	14.8	18.3
May 14	9.0	44.3	45.0	45.0	2.3	5.0	7.3	13.3	4.3	11.7	14.7	19.7
May 1	11.3	37.7	36.0	36.7	2.0	3.0	18.0	63.3	4.3	10.3	16.0	20.0
None (C^1):												
Apr. 1	13.3	42.0	38.8	38.8	2.0	20.0	67.5	120.5	4.3	13.0	19.5	21.0
May 14	11.3	38.7	39.3	39.3	2.0	24.7	83.7	132.3	4.0	13.3	20.0	21.0
May 1	10.3	40.0	38.3	38.3	2.0	24.7	87.0	126.0	4.0	12.7	20.0	20.3
Boron	11.0	26.8	26.0	26.0	2.0	2.0	3.3	3.3	4.0	4.8	6.5	8.5
May 14	11.0	29.0	28.0	28.0	2.0	2.0	4.0	5.5	4.0	4.0	5.5	7.0
May 1	9.7	18.3	32.3	32.3	2.0	2.0	5.7	23.3	4.0	4.0	6.7	10.0
Sulphur	11.0	39.5	33.3	33.3	2.0	4.3	9.0	13.5	4.0	9.8	12.5	15.3
May 14	9.7	35.0	30.0	37.0	2.3	5.0	11.0	32.0	4.0	10.0	13.0	17.7
May 1	10.3	38.0	35.3	35.3	2.0	5.7	38.3	106.7	4.0	10.7	16.3	22.0
Manganese	10.3	42.5	36.5	36.5	2.8	12.3	40.5	72.3	4.3	11.3	15.5	20.3
May 14	11.7	39.0	31.7	31.7	2.0	9.7	40.3	81.7	4.0	11.0	16.0	20.7
May 1	11.7	38.3	36.0	36.0	2.0	9.7	50.7	123.7	3.7	11.0	17.0	21.7
Iron	10.3	15.5	24.3	24.3	2.0	2.8	7.3	15.3	4.0	7.3	12.3	15.3
May 14	9.7	13.7	26.7	26.7	2.0	3.0	11.3	30.3	3.7	8.0	12.3	16.7
May 1	10.0	18.7	40.0	40.0	2.0	2.3	17.7	62.7	3.7	7.7	14.3	18.0
None (C^2)	10.5	38.3	35.5	35.5	2.3	13.8	57.3	122.5	4.0	11.5	17.8	21.3
Do	8.3	37.3	33.3	33.3	2.3	10.3	49.3	113.7	4.0	10.0	15.7	20.7
Do	8.3	35.0	35.7	35.6	2.3	15.7	58.3	109.7	4.0	11.0	17.3	20.7
Chlorine	10.5	38.0	34.0	34.0	2.0	5.8	43.3	106.3	4.0	9.5	15.8	20.8

The air-dry weights, total quantity of water used, water loss per gram of air-dry weight, and percentages of leaf, stalk, and root based on air-dry weight (series 3) are given in Table 7. The data given in Tables 6 and 7 for the group of plants in the incomplete solution and a group of controls similarly placed in the greenhouse represent an average of four plants. The other groups represent an average of three plants. There seems to have been a place effect in the greenhouse so that the averages for control plants are given in groups to correspond with the incompletes and the different periods of change. The control solution designated C^1 was compared with a solution C^2 made up as described under method of experimentation, its calcium being derived from the carbonate and the nitrogen from ammonium nitrate.

TABLE 7.—*Average air-dry weight, volume of water used, and percentage of leaf, stalk, and root for tobacco plants grown in nutrient solutions with and without the different essential elements supplied at intervals, showing recovery during the period April 1 to May 28, 1930 (series 3)*

Elements omitted and date plants were transferred to the control (C^1) solution	Air-dry weight (grams)				Water used (cubic centimeters)		Percentages based on air-dry weight		
	Leaf	Stalk	Root	Total	Total for period	Quantity per gram air-dry weight	Leaf	Stalk	Root
Nitrogen	0.85	0.16	0.30	1.31	641	489	64.9	12.2	22.9
May 14	1.92	.23	.35	2.50	1,091	436	76.8	9.2	14.0
May 1	11.40	4.43	2.50	18.33	7,191	392	62.2	24.2	13.6
Phosphorus	1.35	.16	.55	2.06	1,165	566	65.5	7.8	26.7
May 14	3.07	.33	.77	4.17	1,830	439	73.6	7.9	18.5
May 1	14.08	8.25	4.23	26.56	10,873	409	53.0	31.1	15.9
Potassium	5.55	.43	.56	6.54	4,170	638	84.9	6.6	8.5
May 14	8.83	1.57	1.60	12.00	5,372	448	73.6	13.1	13.3
May 1	16.17	8.35	4.88	29.40	10,884	370	55.0	28.4	16.6
Calcium	1.35	.19	.47	2.01	872	434	67.2	9.4	23.4
May 14	1.55	.20	.66	2.41	1,080	448	64.3	8.3	27.4
May 1	11.50	5.65	2.81	19.96	7,002	351	57.6	28.3	14.1
Magnesium	5.93	.35	.42	6.70	3,818	570	88.5	5.2	6.3
May 14	6.38	.65	.83	7.86	4,024	512	81.2	8.3	10.5
May 1	15.48	6.75	3.92	26.15	9,433	361	59.2	25.8	15.0
Control (C^1):									
Apr. 1	16.51	17.63	6.36	40.50	14,931	369	40.8	43.5	15.7
Do	15.72	19.15	6.80	41.67	15,206	365	37.7	46.0	16.3
Do	18.17	21.20	7.45	46.82	17,140	366	38.8	45.3	15.9
Boron	3.75	.69	.65	5.09	1,780	350	73.7	13.5	12.8
May 14	3.20	.68	.60	4.48	1,637	365	71.4	15.2	13.4
May 1	6.08	2.18	1.27	9.53	3,378	354	63.8	22.9	13.3
Sulphur	8.04	1.89	3.50	13.43	5,310	395	59.9	14.1	26.0
May 14	9.22	3.23	3.50	15.95	7,070	443	57.8	20.3	21.9
May 1	16.52	12.51	5.52	34.55	13,960	402	47.8	36.2	16.0
Manganese	12.51	5.63	2.27	20.41	12,581	616	61.3	27.6	11.1
May 14	14.52	7.50	3.28	25.30	13,543	535	57.4	29.6	13.0
May 1	21.90	16.17	7.10	45.17	16,227	359	48.5	35.8	15.7
Iron	4.27	1.09	.80	6.16	2,762	448	69.3	17.7	13.0
May 14	7.57	3.03	1.98	12.58	4,780	380	60.2	24.1	15.7
May 1	11.92	7.08	2.82	21.82	7,749	355	54.6	32.5	12.9
Control (C^2)	15.32	17.79	5.64	38.75	14,590	377	39.5	45.9	14.6
Do	15.10	15.30	5.75	36.15	13,688	379	41.8	42.3	15.9
Do	15.61	15.42	6.20	37.23	14,285	384	41.9	41.4	16.7
Chlorine	14.29	10.80	4.90	29.99	11,680	389	47.7	36.0	16.3

INTERPRETATION AND DISCUSSION OF RESULTS

It has been shown by studies made in comparatively recent years that the original list of 10 essential elements must be considerably increased if it is to include all elements that are necessary for the normal growth of higher plants. In the older studies on the salts nutrition of plants it was thought that seven elements, namely, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, and iron, in suitable combinations, were all that need be supplied in nutrient solutions. These conclusions were based upon short-time experiments with chemicals possibly containing more impurities than the readily available chemicals of to-day. It has been definitely established that a small quantity of boron and manganese must be present if normal growth is to result. Whether chlorine is essential is still an unsettled question. The elements listed are the ones included in this study. When the tobacco plants were allowed to develop for the periods indicated, in a solution supplying these elements, growth was apparently normal. If other elements such as zinc, aluminum,

and silicon are necessary, as an investigator (*9*, *10*) has reported, the methods used in this study were of such a nature that apparently no adverse effects were manifested in the growth of the plants when these elements were not intentionally supplied in the control solution.

GROWTH IN CONTROL SOLUTIONS

All comparisons and discussions of effects on growth produced when the various elements are lacking in a solution are based on the growth secured in the control solution (C^1). Plants grown in the control solution apparently were normal and showed increased dry weights when compared with the plants grown in the incomplete solutions. They were usually the most economical users of water per gram of air-dry weight, as is shown by Tables 3, 5, and 7. The growth curves (fig. 1, A) for height of tops, based on data given in Table 2 show the effect of renewing the control solution at different periods during growth. The curves for growth in length of roots are shown in Figure 1, B. The growth curves of the tops of plants grown in control solution (C^1) at a different season of the year are shown in Figure 1, C, and in Figure 1, D, the growth curves of the roots, based on data from Table 6. The intervals at which the solutions were renewed are indicated by the dates when the changes were made. The growth curves for plants grown in a second control solution (C^2), where the source of calcium was calcium carbonate and the nitrogen was ammonium nitrate, agree essentially with the curves shown in Figure 1, C and D, and are for this reason not given. It is evident from a comparison of figures given in Tables 6 and 7 that this solution (C^2) produces almost as good growth as the standard control (C^1). The controls when harvested were usually in full flower and in some instances had set a few seed pods. The roots were abundant, much branched, and white to light brown in color. It is evident from a comparison of curves given in Figure 1, A, B, C, and D that the roots make their maximum growth in length before the tops show any considerable elongation.

The curves showing the increase in number of leaves, based on the data given in Tables 2 and 6 for the different solutions, take essentially the same shape as those showing the height of tops of plants and are therefore not presented.

NITROGEN DEFICIENCY

The first incomplete solution to be considered is the one to which no nitrogen was added. Where this element was withdrawn at intervals during the growth of the plant the final product was decidedly reduced, as shown by the figures for air-dry weight given in Table 3, and fell off consistently, depending upon the date of withdrawal of nitrogen. The growth curves given in Figure 2, A, for height of tops based on data from Table 2, serve to demonstrate how soon this effect manifested itself. Where this element was withdrawn during the late stages of growth the total height was not materially reduced. The root-growth curves for these same plants are shown in Figure 2, B. If nitrogen was withheld for a considerable period the ability of the plant to recover was not materially interfered with, for when the plants were transferred to a solution in which this element was supplied, the recovery was rapid and apparently complete, save for the leaves that had dried up. The recovery,

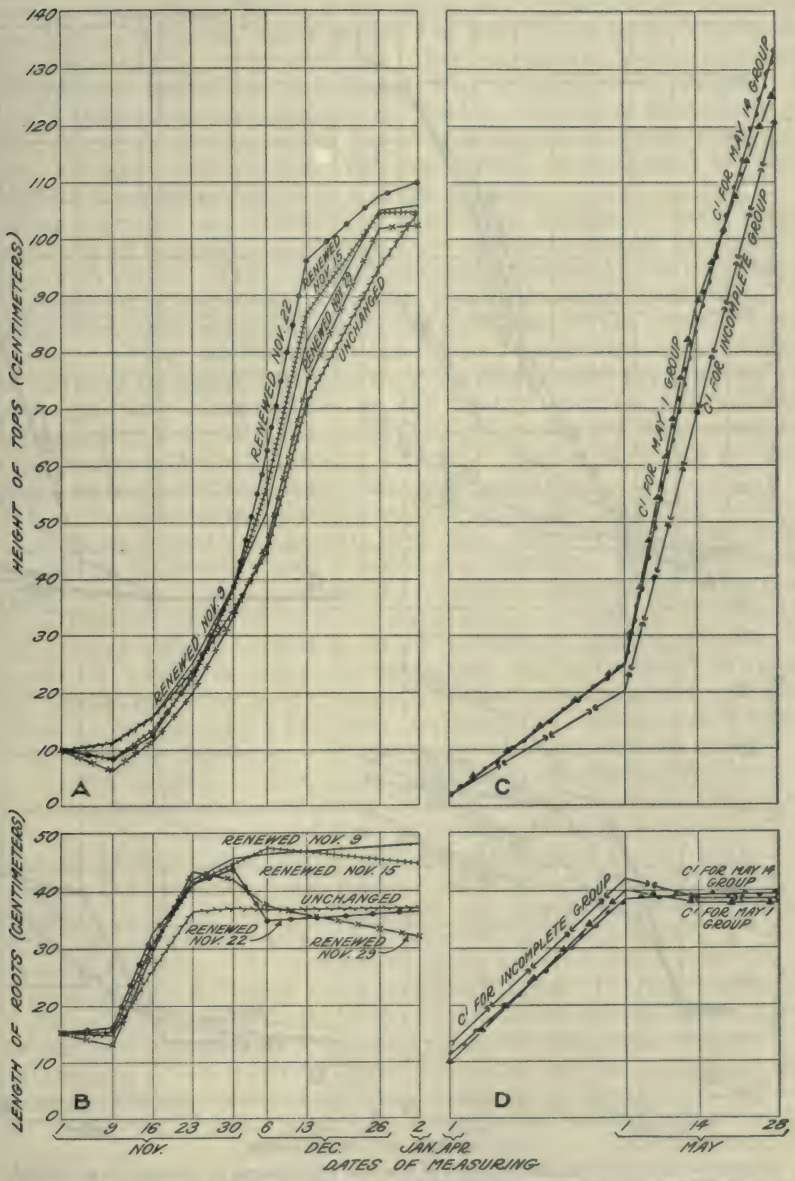


FIGURE 1.—A, Growth in height of plants in control solution (C^1) unchanged and renewed at intervals (Table 2); B, growth in length of roots of plants in control solution (C^1) unchanged and renewed at intervals (Table 2); C, growth in height of plants in control solution (C^1) for different periods of change, located on benches in line with cultures changed as indicated and in incomplete solutions (Table 6); D, growth in length of roots of plants in control solution (C^1) for different periods of change, located on benches in line with cultures changed as indicated and in incomplete solutions (Table 6)

147054—33——3

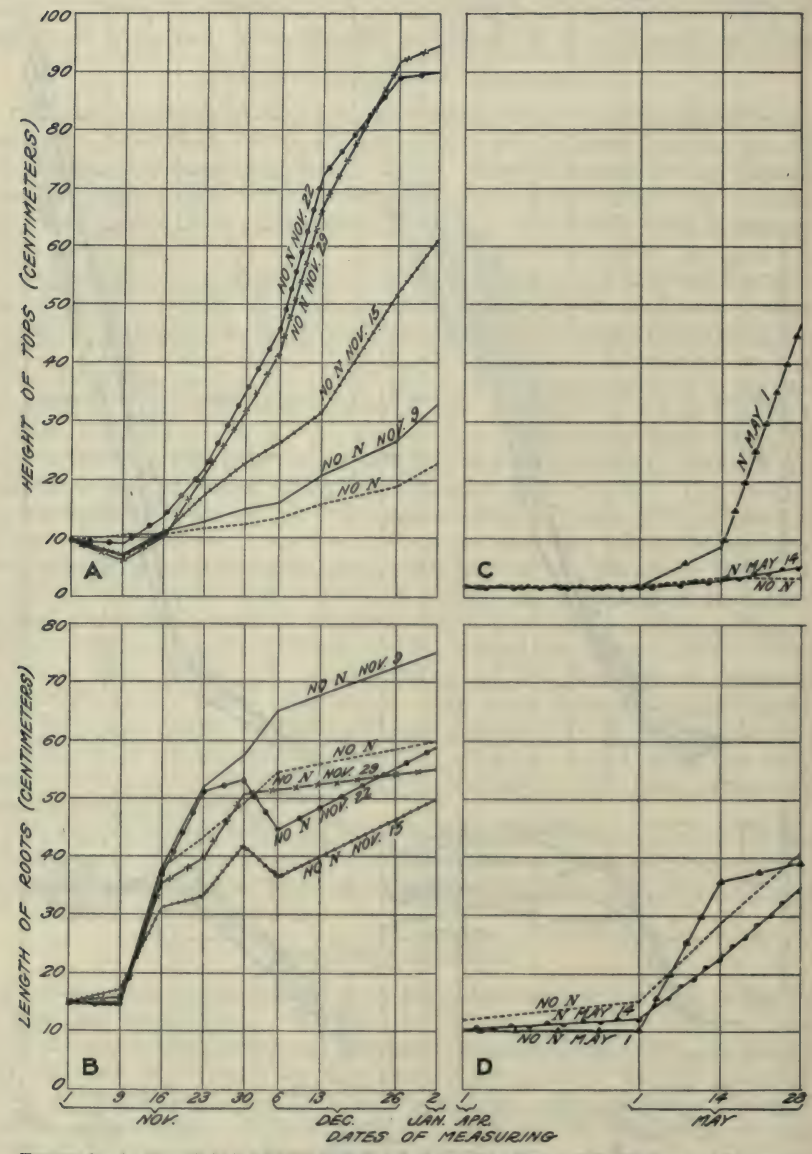


FIGURE 2.—A, Growth in height of plants in solutions with nitrogen (N) withdrawn at intervals, as compared with the growth of plants having no nitrogen during the entire period (Table 2); B, growth in length of roots of plants in solutions with nitrogen (N) withdrawn at intervals as compared with the growth of plants having no nitrogen during the entire period (Table 2); C, growth in height of plants in solutions with nitrogen (N) supplied at different periods, as compared with the growth of plants having no nitrogen (Table 6); D, growth in length of roots of plants in solutions with nitrogen (N) supplied at different periods as compared with the growth of plants having no nitrogen (Table 6)

as indicated by measurements of height of tops plotted as a growth curve, is shown in Figure 2, C, and length of roots in Figure 2, D, based on data from Table 6 for series 3. These curves represent three groups of plants, one of which was held in the no-nitrogen solution for the entire period while the other two groups were transferred to a solution containing this element at two different periods. It appears that where the plants were held in a solution containing no added nitrogen for six weeks they were slower in recovering than where nitrogen was withheld for four weeks, as indicated by their ability to increase in height in a given period.

When nitrogen was withheld or withdrawn during the early stages the growth of the roots appears to have been stimulated, as shown in Figure 2, B and D. This conclusion is substantiated by the percentage of root weight based on total air-dry weight given in Tables 3, 5, and 7, where the root percentage is higher than that of the control. It is evident from the tables that when plants are grown in a solution that contains no added nitrogen they use more water per gram of air-dry weight than plants grown in the control solution although the total quantity is greatly reduced. The percentage of leaf, computed on the basis of the total air-dry weight, is higher than the percentage of leaf in plants grown in the control solution.

While the graphs and data presented show the measurable effects of a deficiency of this element, there are visible phenomena which serve better to identify this condition accurately. When plants are transferred to a solution containing no added nitrogen they lose their normal fresh-green color in a few days, and in a week or 10 days the lower leaves yellow. First a lemon-yellow to orange-yellow color appears on the lower leaves, whereas the bud leaves tend to retain their normal green color, and in no instances have they been observed to show frenching, which has been attributed by Valleau and Johnson (*15*) to nitrogen deficiency. These yellowed leaves dry up or fire to a light-brown color in a few days. The marked effects produced on growth where nitrogen is withheld from the solution are well illustrated in Plate 1, 1. When plants that have been growing in a solution to which no nitrogen has been added are transferred to one containing nitrogen, the recovery takes place rapidly and completely except in the leaves in which the hunger effects are very pronounced or where drying up has taken place. A deficiency of this element produces characteristic firing. Local necrotic spots have not been observed on leaves of plants suffering from nitrogen hunger. If the plants are transferred at a later growth period to a solution containing no added nitrogen they are able to flower and set a few seed pods owing to the translocation of the nitrogen from the older leaves, a transfer that results in their yellowing and drying or firing. However, when plants were transferred from the soil to the solution containing no added nitrogen they remained alive but produced no flowers during the periods of observation.

The stalks of plants suffering from pronounced nitrogen starvation may become somewhat slender and light green in color, but the tendency is for such plants to hold the rosette form with poorly developed stalks. The roots tend to attain a greater length than in the control solution, but there is little or no branching. They are characteristically white in color.

PHOSPHORUS DEFICIENCY

A comparison of the growth of plants in a solution to which phosphorus was added with that of plants grown for a considerable length of time in a solution to which phosphorus was not added showed that the absence of phosphorus caused reductions in growth of plants. (Tables 2 to 7.) The growth curves shown in Figure 3, A, for tops and in Figure 3, B, for roots, based on data given in Table 2, show the effects on growth where this element was withdrawn at intervals. When this element was withdrawn late during the growth there resulted neither reduction in total dry weight produced nor in height of the stalk, nor was there any apparent stimulation in growth as reported by Gericke (*5*). It is evident from the curves shown in Figure 3, C, for tops, based on data given in Table 6, that the ability of the plant to recover is still good after being held in the no-phosphorus solution for six weeks. However, plants did not attain as great a height in the same time as those from which this element was withheld for only four weeks. The graph showing the effect on root growth in length from series 3 is given in Figure 3, D. It is apparent from this graph and from the one shown as Figure 3, B, that when phosphorus is withheld early in growth the root length increases decidedly over that of the control or plant from which phosphorus is withdrawn later in the period of growth. This increase in root growth is substantiated by the high percentage of root in the total air-dry weight shown in Tables 3, 5, and 7. The plants grown in a solution to which no phosphorus is added tend to use a much smaller total quantity of water, but the quantity of water used per gram of air-dry weight is greater than that used by the control. The percentage of leaf based on dry weight is higher than for plants grown in the control solution.

The lack of phosphorus is first shown by the tobacco plant in the development of an abnormally dark-green color, which later develops a brownish cast. The first change in color is apparent within two or three weeks of the transferring of the plants to the solution to which no phosphorus is added. In about four to five weeks a few of the lower leaves may yellow and begin to dry up. When they have dried they are of a greenish-brown or almost black color. Under some conditions, particularly on cultures grown in midwinter, the leaves well up on the plant develop characteristic lesions which are large and lie adjacent to the veins or even cross and include them. These spots are dark brown to black in color. They are not abundant on the individual leaf, usually only a few such areas being found on any one leaf. These leaf spots do not always occur on plants grown in a solution containing no added phosphorus, and it is impossible at the present time to give the exact conditions for their occurrence. Leaves on plants showing phosphorus hunger are characteristically narrow in proportion to their length.

The tendency is for the plant to be held to the rosette form when phosphorus is withheld early in growth. (Pl. 1, 2.) The plants did not flower but remained alive under these conditions for the periods observed. Where the phosphorus is withdrawn after stalk formation has begun, the stalk formed thereafter is slender and weak. Where phosphorus is withdrawn late during growth the plant seems to be able to complete its normal cycle by flowering and setting seed pods. The roots of plants grown in a solution that received no added phosphorus present a characteristic appearance. They are unusually

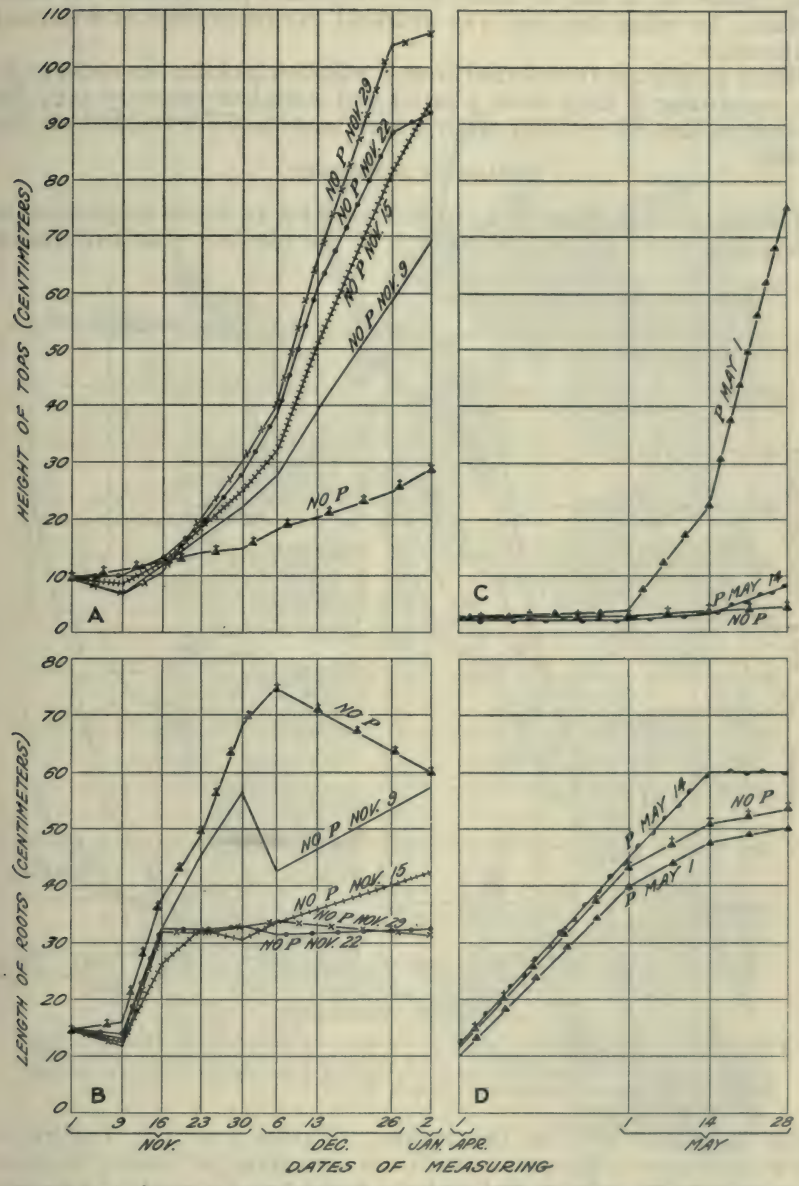


FIGURE 3.—A, Growth in height of plants in solutions with phosphorus (P) withdrawn at intervals as compared with the growth of plants having no phosphorus during the entire period (Table 2); B, growth in length of roots of plants in solutions with phosphorus (P) withdrawn at intervals as compared with the growth of plants having no phosphorus during the entire period (Table 2); C, growth in height of plants in solutions with phosphorus (P) supplied at different periods as compared with the growth of plants having no phosphorus (Table 6); D, growth in length of roots of plants in solutions with phosphorus (P) supplied at different periods as compared with the growth of plants having no phosphorus (Table 6)

long, very little branched, and have a reddish-brown color. This color, however, is due to some iron compound precipitated on their surfaces, for when the iron was withheld the roots were of a normal white color.

When plants are transferred from a solution lacking phosphorus to one containing it they show a rapid and complete recovery save for the leaves that have dried up or where spots have developed on the leaves.

POTASSIUM DEFICIENCY

Tobacco plants grown in a nutrient solution to which no potassium was added were reduced in growth if the element was withdrawn

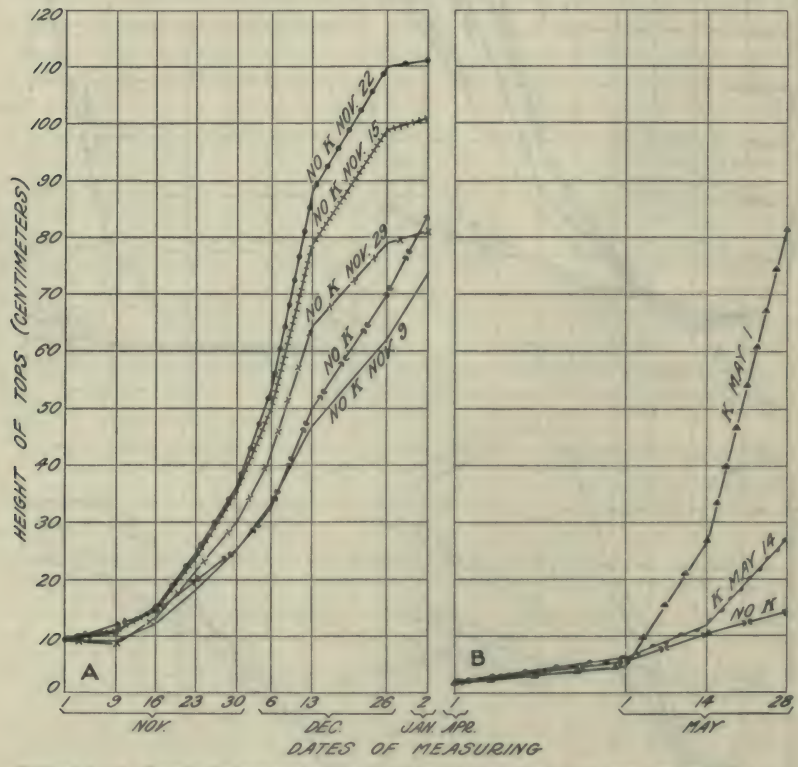


FIGURE 4.—A, Growth in height of plants in solutions with potassium (K) withdrawn at intervals, as compared with the growth of plants having no potassium during the entire period (Table 2); B, growth in height of plants in solutions with potassium (K) supplied at different periods, compared with no potassium (Table 6)

early in the life cycle of the plants. (Tables 2 to 7.) The graph shown in Figure 4, A, constructed from data given in Table 2 for tops, shows the effect of removal of this element at intervals during the growth of the plant. It is evident that these figures are not entirely consistent, in a large measure because of fungi introduced on the roots from the soil. It is characteristic that plants grown in media deficient in this element are more susceptible to injury from parasitic organisms (*11*, *12*). Where this element was withdrawn late in the life cycle there was in some instances no depression in yield. The ability of the plant to recover, as indicated by the graphs given in Figure 4, B, based on data presented in Table 6, was very good;

Tobacco plants placed in culture solutions April 1, 1930, series 3 (photographed May 15, 1930; scale shown in inches): 1, No nitrogen added; 2, no phosphorus added; 3, no potassium added; 4, no calcium added; 5, no magnesium added; 7, no boron added; 8, no sulphur added; 9, no manganese added; 10, no iron added; 6, all of above elements added

Lith. A. Hoen & Co.

while the graph showing recovery after the plant had been held in a solution without potassium for six weeks does not exactly parallel the recovery after four weeks, it approximates it. The curves showing root growth in length of these plants take essentially the same shape as the corresponding curves of the control plants (fig. 1, B and D) and are, therefore, not presented. The quantity of water used per plant is reduced when potassium is withheld early enough to dwarf the plant, but the quantity of water necessary to produce 1 gram total air-dry weight is materially increased as compared with the control. The percentage of leaf, based on the air-dry weight, is materially greater than in the case of the control.

The characteristic effects on growth resulting from a deficiency of potassium have received early (*16*), and possibly more, attention (*11*) than those of any of the other elements. These characteristics will be described here with an attempt at greater detail for purposes of comparison with other deficiency symptoms when growing conditions are similar for all the plants. The first symptom of potassium deficiency, as shown by the tobacco plant, is the development of abnormally dark-green color with a bluish cast, followed characteristically by a chlorosis or yellowish mottling of the lower leaves. This mottling usually appears at the tips and margins of the older leaves, and is typically followed by a dying of the tissue within the mottled area, thus giving the plant a rusty appearance. These dead areas are characteristically very small at first although they later may enlarge and coalesce until most of the leaf tissue between the principal veins is involved. A typical case of a plant with potassium hunger contrasted with a normal plant is shown in Plate 1, 3 and 6. In cultures grown in midwinter these effects do not always take the above-described characteristic course in that the final change resulting in a drying up of the tips and margins of the leaves, though delayed, appears so rapdily that it is impossible to distinguish the intermediate steps. In all cases observed the bud leaves tended to remain normal while the older leaves showed the characteristic effects, and in extreme cases the primary and secondary veins became shriveled and the leaf apparently lost its turgor and hung down against the stalk. The leaves are markedly cupped under at the tips and margins. A few bottom leaves may finally dry up, but the spots still persist. When plants that show decided potassium hunger are transferred to a solution containing this element all new growth is normal and all old leaves recover, save in the necrotic areas. This results in a decided rim-bound condition on such leaves.

The stalks of plants suffering from extreme potassium hunger after a time show lesions, usually just below or around the point where the leaf is attached to the stalk. Where the plant was transferred from the soil to a nutrient solution containing no added potassium the stalk was poorly developed and slender. Such plants were unable to flower and set seed though they did not die during the period of observation. The roots from these plants were relatively long and had very few branches. They manifested a yellowish slimy appearance.

MAGNESIUM DEFICIENCY

The effect of a deficiency of magnesium on the growth of the tobacco plant is marked. A decreased growth resulted when this element was withdrawn at all periods, as is shown by the data pre-

sented in Table 3 giving dry weights. The later withdrawals did not cause a marked reduction, however. The growth curves for heights of tops as given in Figure 5, A, based on data presented in Table 2, show about the same relations as the final dry-weight data. The curves showing the recovery when this element is withheld for different periods are given in Figure 5, B, for tops, based on data given in Table 6. It is evident from these curves that the plant recovers rapidly when this element is supplied after it has been withheld for a time. However, the recovery is more rapid at the end of four weeks than after six weeks, as indicated by the height attained in a given period. The curves showing root growth in the above cultures take practically the same shape as the control given in Figure 1, B and D, and for this reason are not given.

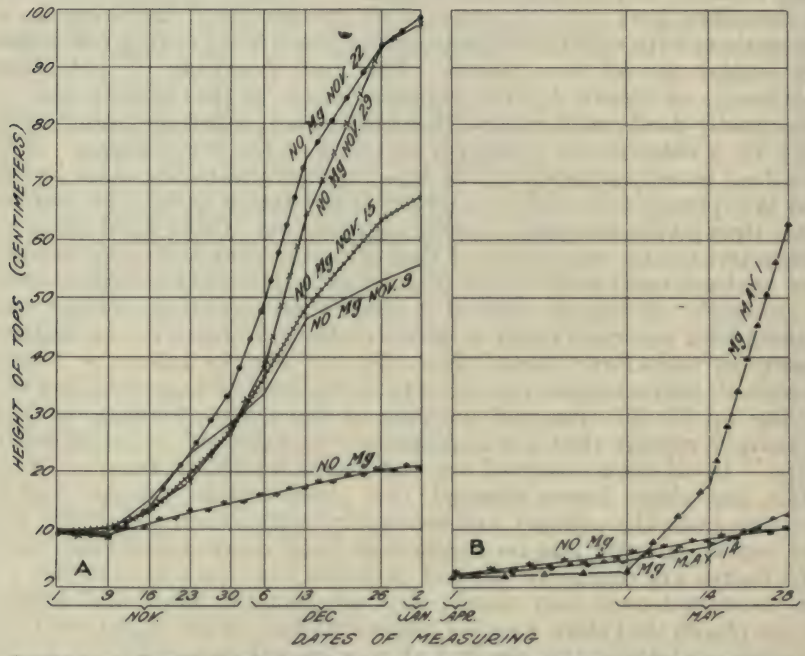


FIGURE 5.—A, Growth in height of plants in solutions with magnesium (Mg) withdrawn at intervals, as compared with the growth of plants having no magnesium during the entire period (Table 2); B, growth in height of plants in solutions with magnesium (Mg) supplied at different periods, compared with no magnesium (Table 6)

If this element was withheld early enough in the life cycle to cause a decided reduction in growth the total quantity of water used by the plant was lowered, but the quantity necessary to produce 1 gram of total air-dry weight was increased.

The measurable effects presented above show decided retardation where this element is withheld early in growth. However, these effects are not as characteristic as the appearance of the plants. The plants when transferred to a solution containing no added magnesium, in two to three weeks began to show a chlorosis or loss of the green color on the lower leaves of the plant between the veins. Here the loss of color as seen under field conditions, is not so characteristically confined to the lower leaves or to the leaf tips and margins as in the instances of this deficiency previously described (*1*, *4*, *11*). In fact,

in some instances, one, two, or more, mature leaves failed to lose their green color. First the leaves became a light green, but later the leaf tissue became almost white between the principal veins, which tended to retain their normal green color. It is characteristic of these leaves in the later stages to curl upward at the tips and margins, and the principal veins become shriveled so that the leaves apparently lose their ability to support themselves and hang down against the stalk. A typical case of a plant showing magnesium hunger as contrasted with a normal plant is presented in Plate 1, 5 and 6. All leaves on the plants, save the bud leaves, may finally become involved. In all cases observed the bud leaves tended to remain normal. Where magnesium was removed late in the growth period the plant was able to flower and set seed but when removed early no flowers or seed were formed, and a rosette condition resulted, induced by a shortage of this element. Such plants showed an exceptionally high percentage of leaf, computed on the basis of the air-dry weight, as compared with the percentage of leaf in plants in all other cultures.

Under some conditions the leaves on plants showing magnesium hunger developed large lesions even prior to the appearance of the characteristic chlorosis. This condition seems to be common on cultures grown in midwinter or when the plants that had been growing vigorously in the control solution were transferred to the solution to which no magnesium had been added. Leaves suffering from pronounced magnesium hunger rarely dry up.

When plants which are showing pronounced symptoms of magnesium hunger are transferred to a solution containing this element the new growth produced is normal, and the chlorotic leaves recover their normal green color, although the older leaves are very slow in recovering. The stalks of plants suffering from pronounced magnesium hunger are slender and may show lesions just below or around the point where the leaves are attached. The roots are few in number and have a relatively small number of branches. They are comparatively long and slimy in appearance.

CALCIUM DEFICIENCY

Effects of the lack of calcium, as manifested by the growth of the tobacco plant, are pronounced. The result of withdrawal of this element is shown by the growth of the plants, as illustrated by Figure 6, A, for height of tops, based on data given in Table 2. If this element is withdrawn early in the growth period there is almost no increase in height, and the total height reached is in direct proportion to the time of removal. The falling off in total dry-weight production, as given in Table 3, is also directly dependent upon the extent of the period during which this element was supplied, although the late removal has not reduced the dry weight. Figure 6, B, based on data given in Table 2, shows that the length of the roots is reduced according to the time of removal of this element, the roots being shorter where this element was removed at an early stage of growth. The recovery of plants where this element was withheld for different periods is shown in Figure 6, C, based on data given in Table 6. When this element is withheld for an extended period, the recovery

of the plant is slow. The roots are small, as shown in Figure 6, D, which may explain the slow recovery.

That the percentage of the total dry weight of leaf is fairly high when compared with that of the control, is shown by the data in Tables 3,

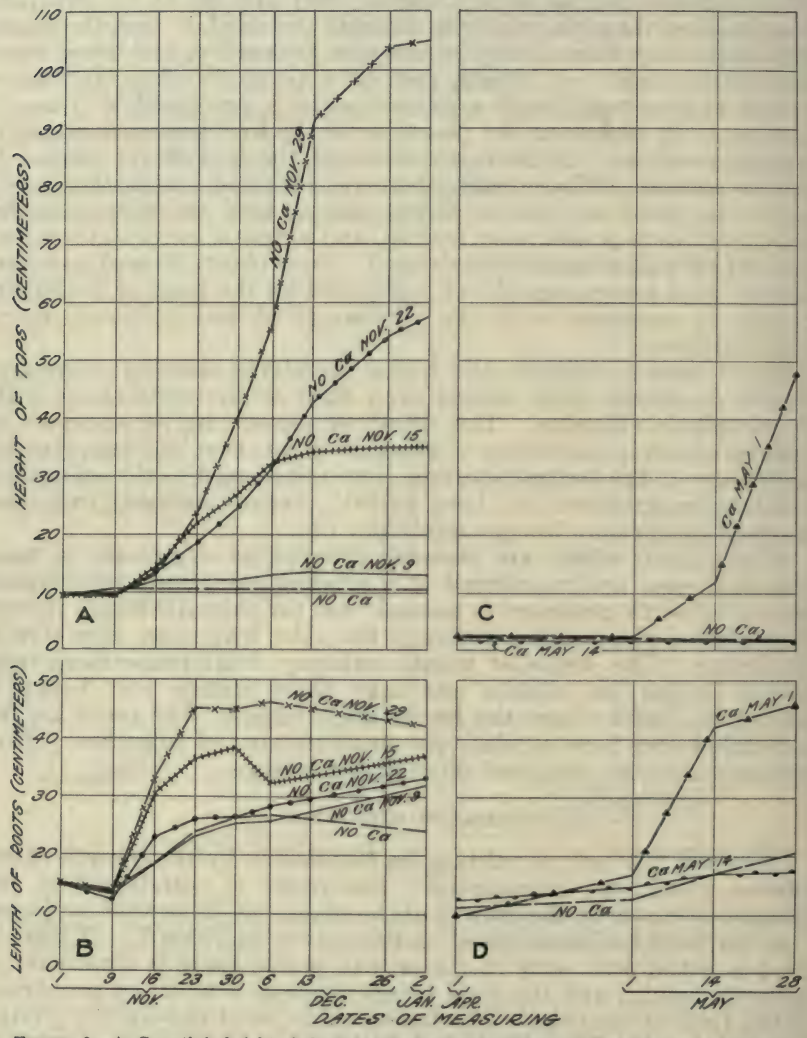


FIGURE 6.—A, Growth in height of plants in solutions with calcium (Ca) withdrawn at intervals, as compared with the growth of plants having no calcium during the entire period (Table 2); B, growth in length of roots of plants in solutions with calcium (Ca) withdrawn at intervals, as compared with the growth of plants having no calcium during the entire period (Table 2); C, growth in height of plants in solutions with calcium (Ca) supplied at different periods, as compared with the growth of plants having no calcium (Table 6); D, growth in length of roots of plants in solutions with calcium (Ca) supplied at different periods compared with no calcium (Table 6)

5, and 7. The root percentage is also higher than would be expected from the length of the roots. The total quantity of water used is reduced where this element is removed early enough to produce marked dwarfing, but the amount of water necessary to produce 1 gram of dry weight is not materially greater than that in the control.

Characteristic effects on growth are usually apparent within 10 to 14 days of the removal of this element. If the plants are transferred early, the first effect is a peculiar hooking downward of the young leaves making up the bud at their tips. This is followed by the death of the young leaves characteristically at their tips and margins, and if growth later takes place the tips and margins are missing, which gives the leaves a cut-out appearance. This is one of the symptoms seen under field conditions (*2*). The plant, as a whole, is an abnormally dark-green color, and the leaves are somewhat thickened as the result of death of the terminal bud. In the later stages all terminal growth is stopped, and some necrotic spots and chlorosis may develop on the older leaves, but this is not characteristic. Where the plants are transferred late in the life cycle to a nutrient solution containing no added calcium so that the effects of its absence are not manifested by the plant until the flowering stage, the plants show a drying up of the corollas at their tips, so that eventually the pistil protrudes and the calyx lobes may also show necrotic spots. Such plants may set a few seed pods, but the tendency is for most of the flowers to shed before seed pods are set. Death of the terminal buds results (pl. 1, 4) if calcium is removed early in the growth period, and no flowers are formed.

When such plants are transferred to a nutrient solution in which this element is supplied, the recovery is slow, and the tendency is for the plant to develop one or more suckers, since the apical dominance has been broken up owing to the death of the terminal bud. The new growth which is produced for a time may show abnormally shaped leaves, but later the leaves produced are of a normal shape.

The stalk growth is materially reduced in length when this element is withdrawn early in the life cycle, and when once stopped it is unable to renew its growth by translocation of this element from the older parts of the plant. Lateral buds may start at the axils of the leaves, but they immediately develop the above-described effects and die back. The roots are short and thick and show many branches. They are usually a dirty-brown color and more or less decomposed. In some instances plants suffering from extreme calcium hunger were not able to survive the period of the experiment.

BORON DEFICIENCY

The effect of boron deficiency on the growth of the tobacco plant has been reported in a previous paper (*8*). Further studies of the effects of a deficiency of this element on growth were made in this series of experiments along with studies of the other deficiencies to determine where its effects differ or resemble those of the other elements. The graph based on data from Table 2, presented in Figure 7, A, shows how soon at different periods in the life cycle the withholding of this element manifests its effect on the growth in height of the plant. The increase in height is in direct proportion to the time of removal. The root-growth curves (fig. 7, B), based on data from Table 2, show that the length is affected by the early removal of this element. The recovery of plants when this element is withheld for a time is shown in Figure 7, C, based on data from Table 6. It is evident that the recovery is slow where this element is withheld for four weeks and that where it is withheld for six weeks the ability of the plants to recover, as indicated by increase in height in a given

period, is materially injured. The root-growth curve for these same plants is shown in Figure 7, D. It appears from this graph that the roots of these plants are considerably shorter than those of the controls. (Fig. 1, B and D.)

The percentage of leaf in the total dry weight (Tables 3, 5, and 7) is materially increased when this element is withheld early in the growth period, while the stalk percentage is decreased without great

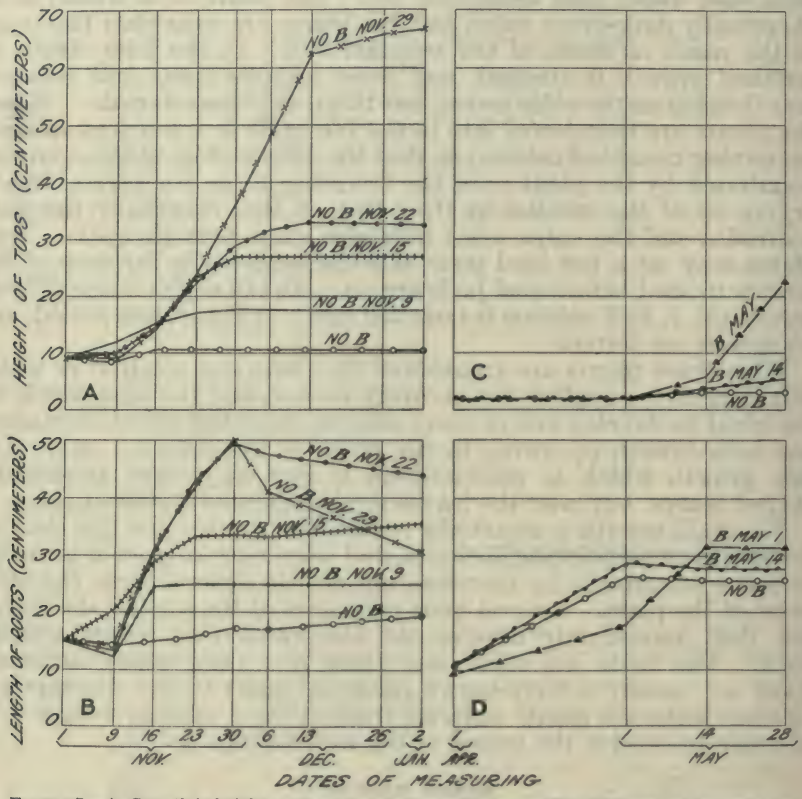


FIGURE 7.—A, Growth in height of plants in solutions with boron (B) withdrawn at intervals, as compared with the growth of plants having no boron during the entire period (Table 2); B, growth in length of roots of plants in solutions with boron (B) withdrawn at intervals, as compared with the growth of plants having no boron during the entire period (Table 2); C, growth in height of plants in solutions with boron (B) supplied at different periods, as compared with the growth of plants having no boron (Table 6); D, growth in length of roots of plants in solutions with boron supplied at different periods as compared with the growth of plants having no boron (Table 6)

change in root percentage. The total quantity of water used by the plant is small, and the amount per gram of dry weight is even less than for plants grown in the control solution.

The effects of boron deficiency were usually apparent within a week or 10 days of the transferring of the plants to a nutrient solution lacking this element. The first visible effect was the manifestation of a light-green color of the leaves making up the bud with the base of the individual leaf assuming a lighter green than the tip. When this appears the bud has ceased to grow and has a somewhat drawn appearance. This is followed in a day or so by a breaking down of the tissue at the base of the young leaves making up the bud. When

this stage does not progress too far and if the young leaves later make some growth they will look distorted because of the growth around this injured tissue. The death of the terminal bud (pl. 1, 7) was the final result of the above-described phenomena. This automatic topping causes the individual leaves to thicken and increase in area. When this takes place lateral buds may develop in the axils of the leaves or even on the base of the stalk or the roots, but they break down, as described above. The leaves remaining on such plants are glabrous and brittle, and when they are broken the vascular tissue is blackened. The upper leaves of the plant tend to roll in a half circle from the tip toward the base. They are of an unhealthy light-green color. Such plants were again (*8*) observed to emit a faint aromatic odor resembling the tobacco-blossom odor. If this element was withdrawn late in the life cycle of the plant so that the shortage was felt at the blossoming stage, usually all the flowers were shed and no seed pods set.

If plants suffering from decided boron hunger were transferred to a nutrient solution containing this element they were slow in recovery and, because of the destruction of the apical dominance as a result of the death of the terminal bud, they developed, as a rule, more than one sucker. In most cases the growth first produced was of leaves abnormal in shape, but leaves produced later were normal.

The stalks of plants suffering from boron deficiency were not able to elongate further, once the effect of the deficiency was apparent. The roots of plants suffering from boron hunger have many short branches, but the primary roots may be relatively long and brownish in color and may be somewhat decomposed. In one or two instances plants suffering from extreme boron hunger did not survive the period of the experiment.

SULPHUR DEFICIENCY

The effect of a lack of sulphur on the growth of the tobacco plant is illustrated by Figure 8, A, based on the data from Table 2, which shows the effect of the withdrawal of this element at intervals during the growth of the plant. The early withdrawal of this element resulted in decided reductions in height of tops, but very late withdrawals did not always do so. The dry-weight figures given in Table 3 take much the same course. These figures are not entirely consistent, as fungi injured some plants more than others. It was characteristic of the cultures in which this element was withdrawn in this series that a practically pure culture of *Thielavia basicola* developed although the pH of the fresh solution was distinctly acid or about the same as that of the control in which practically no evidence of this organism was seen. It is generally known that this organism thrives in a neutral or alkaline medium, but in this case this appears not to be the explanation. In series 3, where this organism was not present owing to disinfection, the growth was materially reduced when this element was withheld. Recovery took place rapidly and completely when it was supplied, as is shown by the curves given in Figure 8, B, based on data from Table 6. The curves showing the root growth resemble so closely the curves for roots of the controls (fig. 1, B and D) that it was not considered necessary to give them. The percentage of roots in the total dry weight was higher than that for the controls, as was also the percentage of leaf. If this element were removed early

enough to produce a reduction in growth the total quantity of water necessary for the plant was also reduced, but the quantity necessary per gram of air-dry weight as compared with the control was not materially changed.

The typical effect on growth produced when sulphur was deficient manifested itself first in the light-green color of the younger leaves on the plant. The older leaves retained their normal green color (pl. 1, 8), but the younger leaves were of a light-green color, and the veins were characteristically lighter in color than the intervein areas of the leaf. This effect became apparent within from two to three weeks of the transferring of the leaves to the solution that contained no added sulphur. If the transfer were made late or just prior to the flowering

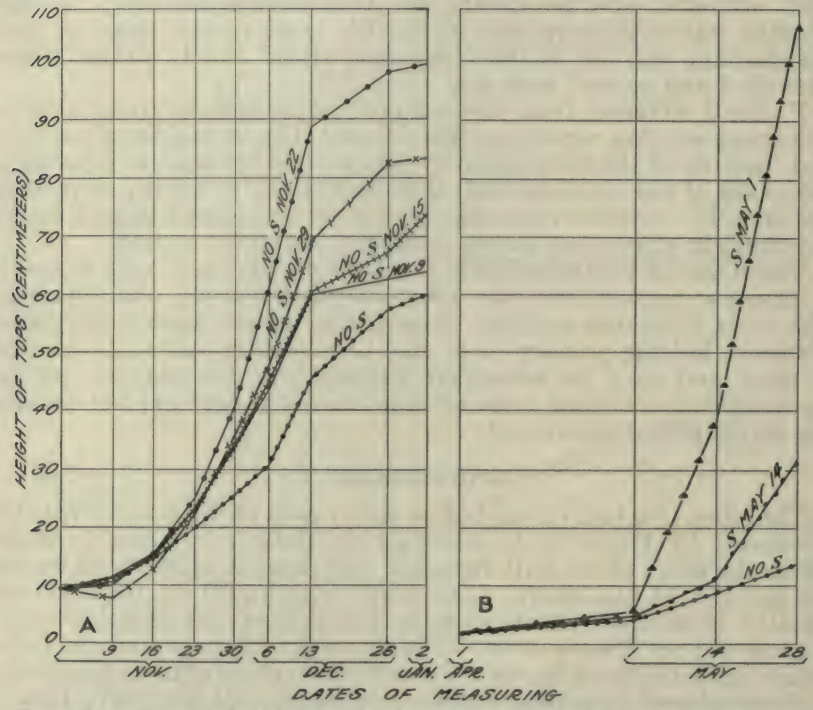


FIGURE 8.—A, Growth in height of plants in solutions with sulphur (S) withdrawn at intervals, as compared with the growth of plants having no sulphur during the entire period (Table 2); B, growth in height of plants in solutions with sulphur (S) supplied at different periods as compared with the growth of plants having no sulphur (Table 6)

stage such plants were able to flower and set seed although the quantity produced was reduced. If the plants were held from an early period in their life cycle in a solution containing no added sulphur they were unable to flower during the period of observation. However, if such plants were transferred to a nutrient solution containing sulphur they showed almost immediate recovery and no harmful effects from having been held from four to six weeks in a solution deficient in this element.

The stalks of such plants show no striking abnormalities save possibly a lighter green color. The roots, however, are characteristic in their appearance. They are abundant and much branched and are typically of a white color if no parasites are present. Plants from

which sulphur was withheld early in the growth period tended to hold the rosette condition and were unable to flower or set seed although they were able to remain alive during the period of observation.

IRON DEFICIENCY

The growth curves presented in Figure 9, A, based on data given in Table 2, represent the effects on growth in height when iron was removed at intervals during the growth of the plant. When this element was withheld early in growth there was a marked reduction in height, although later removals do not always appear to reduce the final height. The roots were shorter where iron was withheld early during growth than in the control solution as shown by Figure 9, B, based on data from Table 2. The results in this case were not entirely consistent which appeared to be due to parasitic organisms being accidentally introduced in some instances and possibly causing more damage because of the absence of iron salts which are known to have mild fungicidal properties.

The recovery of plants grown without iron for a time and then supplied with this element is shown in Figure 9, C, for height of tops, and in Figure 9, D, for length of roots, based on data from Table 6. It is evident that the recovery after six weeks is just as rapid as after four weeks, as indicated by the heights attained in a given period.

The total quantity of water used decreased when this element was withheld early enough to produce any considerable dwarfing of the plant, but the quantity of water necessary per gram of total dry weights increased considerably as compared with the quantity used by the control. The percentage of leaf in the total dry weight increased.

The typical chlorosis caused by an insufficient quantity of iron was one of the first deficiency diseases of plants to be recognized (7). In fact, the term chlorosis has been used so frequently in this connection that iron deficiency and chlorosis in plants have often been treated as synonymous terms. This chlorosis is characteristic and manifests itself first on the young leaves making up the bud. These leaves first lose their green color between the veins and become light green to white in color. (Pl. 1, 10.) The lower leaves on the plant will be of a normal green color, and the veins of the younger leaves tend to retain their green color. However, the leaves making up the bud may eventually become perfectly white. This chlorosis usually develops in from three to four weeks when iron is withheld during the early growth of the plants. If the iron was withheld after one month such plants rarely showed chlorosis but flowered and set seed normally. These chlorotic leaves usually show no lesions, but under some conditions when exposed to bright sunlight and dry air they tend to dry up.

If plants which show pronounced symptoms of iron hunger were transferred to a solution in which this element was supplied they tended to assume their normal green color. All the growth produced following the transfer will be normal although some of the older chlorotic leaves may not develop a green color and in this case a chlorotic leaf may be seen on the lower part of the plant.

By withholding iron it is possible to prevent any considerable stalk development and the flowering of the plant. The roots on such plants are relatively short and have many short branches. Such plants remained alive during the period of the experiment.

MANGANESE DEFICIENCY

The effects of a shortage of manganese on height of plants is shown in Figure 10, A, which is based on data from Table 2. When this

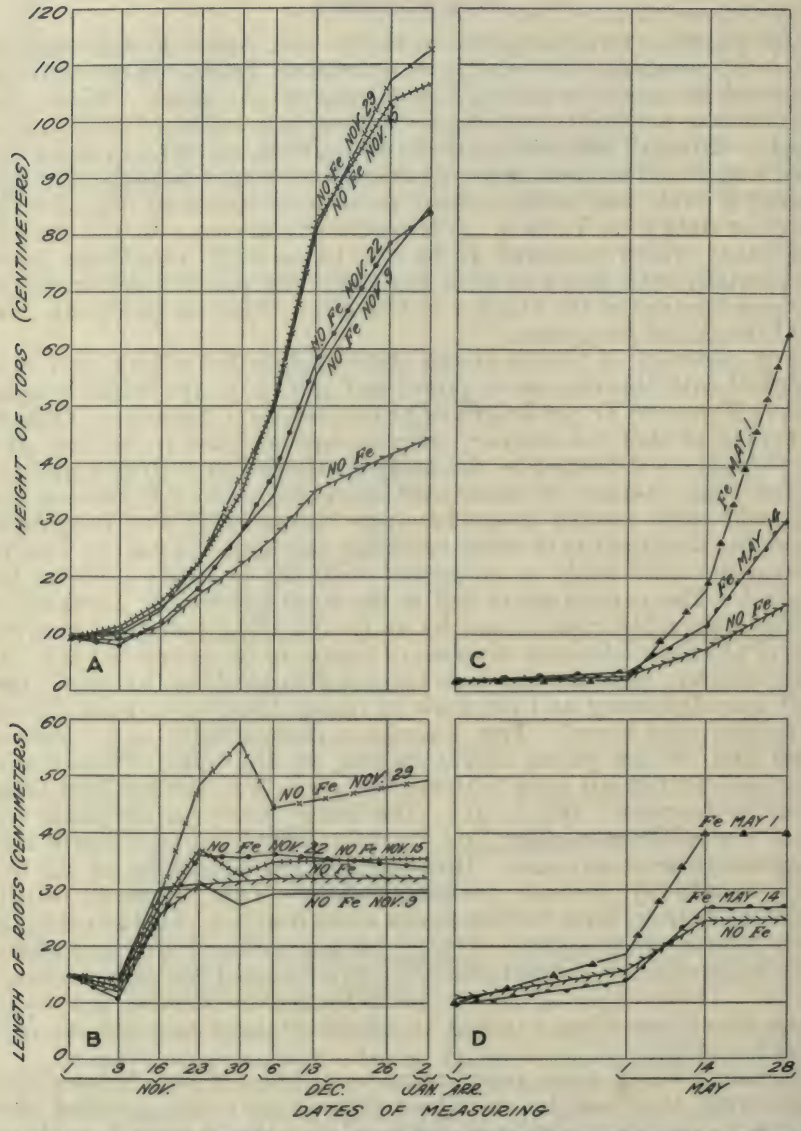


FIGURE 9.—A, Growth in height of plants in solutions with iron (Fe) withdrawn at intervals, as compared with the growth of plants having no iron during the entire period (Table 2); B, growth in length of roots of plants in solutions with iron (Fe) withdrawn at intervals as compared with the growth of plants having no iron during the entire period (Table 2); C, growth in height of plants in solutions with iron (Fe) supplied at different periods as compared with the growth of plants having no iron (Table 6); D, growth in length of roots of plants in solutions with iron (Fe) supplied at different periods, as compared with the growth of plants having no iron (Table 6)

element was withheld early in the life cycle of the plant a reduction in total height resulted. The root growth of the plants was also affected, as is shown by Figure 10, B. The recovery of plants is

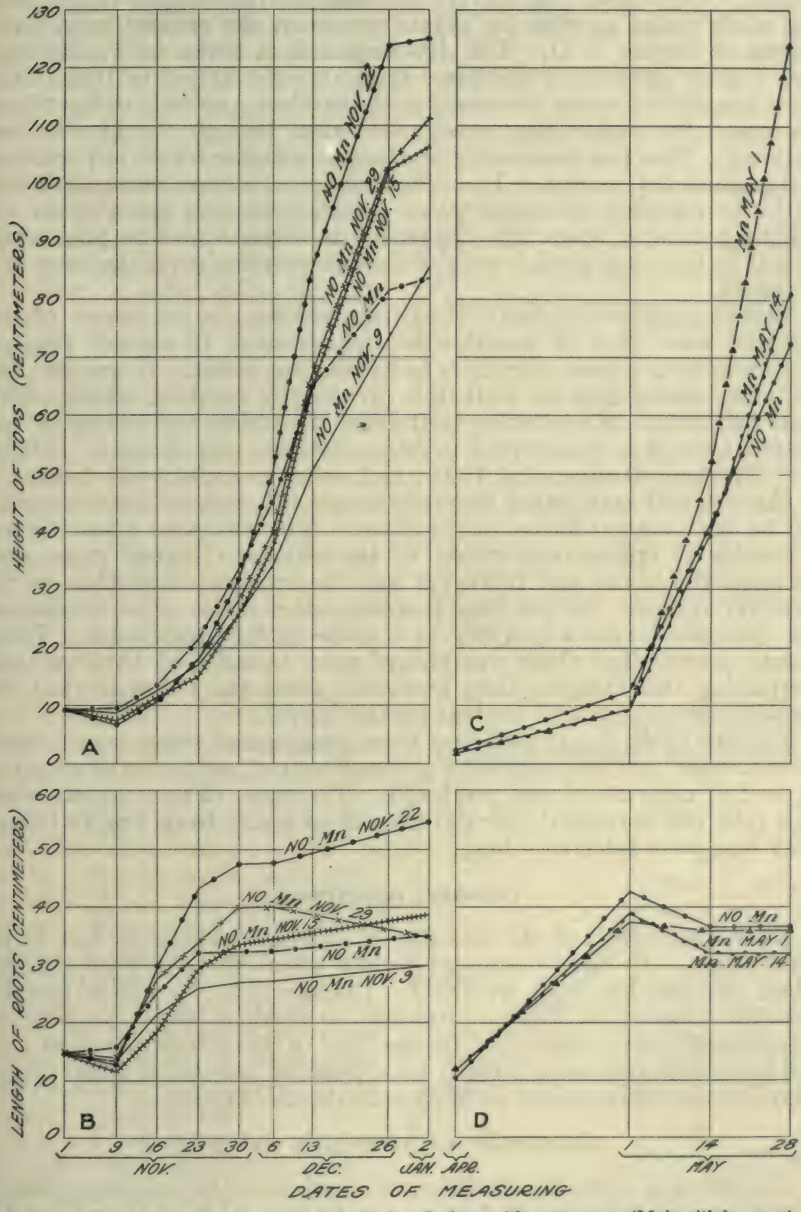


FIGURE 10.—A, Growth in height of plants in solutions with manganese (Mn) withdrawn at intervals, as compared with the growth of plants having no manganese during the entire period (Table 2); B, growth in length of roots of plants in solutions with manganese (Mn) withdrawn at intervals, as compared with the growth of plants having no manganese during the entire period (Table 2); C, growth in height of plants in solutions with manganese (Mn) supplied at different periods, as compared with the growth of plants having no manganese (Table 6); D, growth in length of roots of plants in solutions with manganese (Mn) supplied at different periods, as compared with the growth of plants having no manganese (Table 6)

shown in Figure 10, C, based on data from Table 6 on the increase in height. The curve (fig. 10, D) showing the root length takes much the same shape as that for plants grown in the control solution as shown in Figure 1, D. The dry-weight data given in Tables 3, 5, and 7 show practically the same trends as the height of tops. The total quantity of water necessary per plant does not seem to have been decreased by withholding manganese even though the growth was reduced. This has necessarily resulted in a higher water requirement per gram of dry weight. This effect agrees with the findings of Mazé (*9*), who reported increased water consumption per gram of air-dry weight produced when this element was withheld. The percentage of leaf in the total air-dry weight was increased when manganese was withheld.

The characteristic effects which resulted from a deficiency of this element were slow in manifesting themselves. It usually requires from four to five weeks for them to become apparent. It was possibly for this reason that no reduction in growth resulted where plants that had grown in a solution containing no added manganese for one month were then transferred to one containing the element. (Table 6.) The typical effects (pl. 1, 9) which occur as a result of a deficiency of this element manifested themselves as a chlorosis which was apparent on the younger leaves of the plant. This chlorosis gives the leaf a checkered appearance owing to the chlorosis taking place only between the veins and following out the minutest branches of the vascular system. In the later stages small necrotic spots develop on the chlorotic leaves which dry to a white or brownish color. When plants manifesting these symptoms were transferred to a solution containing this element they recovered from the chlorosis, but the necrotic spots were still evident on the leaves.

The stalks of plants suffering from pronounced manganese hunger were slender, and although such plants flowered, only a small quantity of seed or none at all was produced. The roots of such plants were, as a rule, not abundant, nor did they show many branches, but those they had were relatively long.

CHLORINE DEFICIENCY

No typical effect of the absence of chlorine on growth has so far been found. In some instances growth seems to have been reduced when chlorine has been withheld. (Tables 2 to 7.) It is possible that the absence of chlorine produced no marked effects because the experiments were conducted in the city of Washington where considerable soft coal was burned in a near-by industrial plant which supplied the surrounding air with considerable chlorine.

COMPARISON OF DEFICIENCY EFFECTS

It is evident from the foregoing discussion of the deficiency effects of the several elements that there are points in which they resemble one another. All of the deficiencies result in reductions in growth, as illustrated by the total dry matter produced. (Tables 3, 5, and 7.) The growth curves from series 3 (fig. 11, A), based on data from Table 6, show the typical reductions in growth of height of tops when the several elements are deficient as compared with growth obtained in the controls. The effects on root growth are shown in Figure

11, B, for the same plants. In this case some stimulation of root growth appears to have taken place when certain elements are withheld. This effect is also apparent in Figure 12, where the percentages of root, stalk, and leaf are shown on the basis of averages for the three series grown in the standard solutions. Here the longest root gives the highest percentage of root calculated on the basis of the air-dry weight. However, a long root did not always mean a high percentage of root based on dry weight. For example, the plants that showed magnesium deficiency had a relatively long root but showed the lowest percentage of root. The plants suffering from magnesium and potassium hunger had a relatively high percentage of leaf. It was characteristic of those cultures that showed a high water loss per gram of air-dry weight to show a high percentage of leaf, although there were two outstanding exceptions. The plants that suffered from manganese hunger and gave the highest water loss and the plants suffering from boron hunger and showing the least loss of water per gram of air-dry weight were both relatively high in leaf percentage, though they were neither the highest nor the lowest in percentage of leaf.

There are two points of similarity in symptoms produced which enable one to make two classifications which serve for the broader distinctions. The first group of elements, including nitrogen, phosphorus, potassium, and magnesium, characteristically manifest deficiency effects on the older growth. The second group of elements, including calcium, boron, sulphur, iron, and manganese, typically show deficiency effects on the new growth. It appears from this classification that the elements making up the first group are more mobile than are those making up the second group.

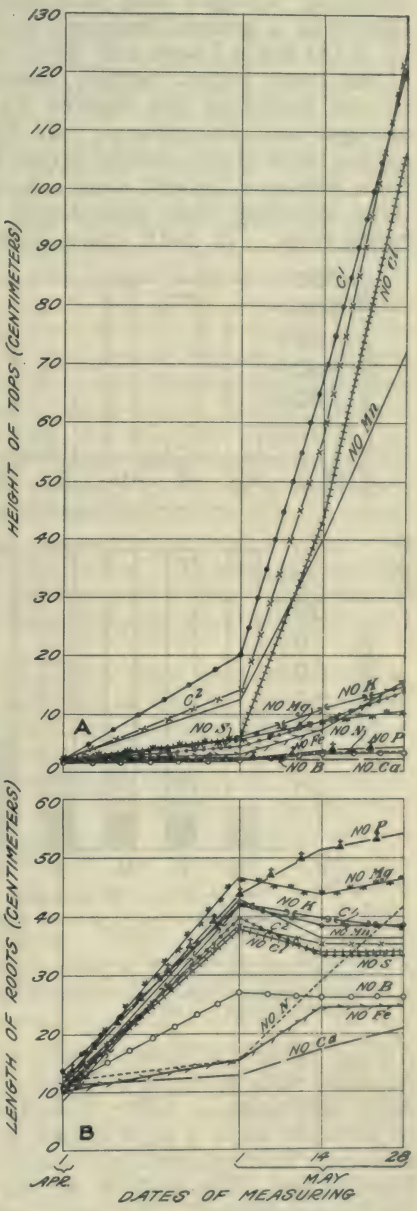


FIGURE 11.—A, Growth in height of plants in control solutions (C^1) and (C^2) as compared with the growth of plants in solutions deficient in the different essential elements (Table 6); B, growth in length of roots of plants in control solutions (C^1) and (C^2) as compared with the growth of plants in solutions deficient in the different essential elements (Table 6)

The first group may be further subdivided into those elements, including nitrogen and phosphorus, that manifest their deficiency effects as a general dwarfing, with yellowing followed by the drying up of the lower leaves and those causing local effects such as chlorosis of the lower leaves, namely, potassium or magnesium. The general effects, including the decided dwarfing resulting from shortages of nitrogen and phosphorus, may be distinguished one from the other on the basis of the general appearance of the plant. Plants suffering from nitrogen hunger show an abnormally light-green color, while those suffering from phosphorus hunger show an abnormally dark-green color. In both cases there is some yellowing and firing or

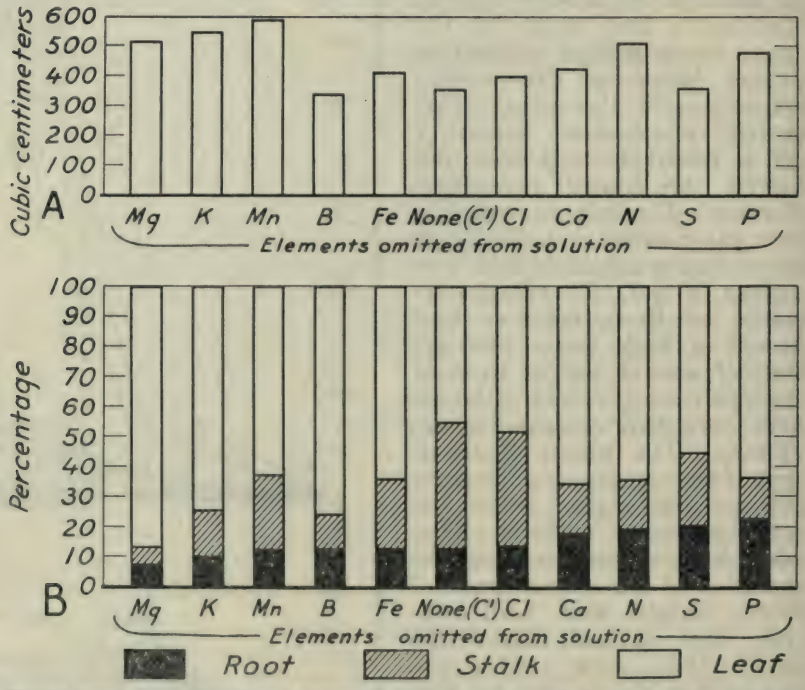


FIGURE 12.—A, Average number of cubic centimeters of water transpired per gram of total air-dry weight of plants from plants in series 1, 2, and 3 grown in standard group of solutions; B, average percentages of leaf, stalk, and root in total air-dry weight of plants grown in standard group of solutions in series 1, 2, and 3

drying up of the lower leaves, but this effect is usually more pronounced with nitrogen deficiency. However, the leaves after drying show differences in color, those from plants suffering from a shortage of nitrogen show a light brown as contrasted with those from plants suffering from phosphorus hunger, which show a greenish-brown to black color. The stalk is slender and short in extreme cases where both are deficient. If either of these elements is removed late during the period of growth, flowering and setting of seed take place, although the number of seed set may be reduced. The roots resemble each other in that they are relatively long and little branched, but where the plant is suffering from nitrogen hunger they are white, and where phosphorus is withheld they are of a reddish-brown color.

The local effects manifesting themselves on the lower or older leaves as mottling or chlorosis are characteristically due to potassium or magnesium hunger, which may be distinguished by the fact that with the former the mottled areas usually surround small necrotic spots or specks which are located at the tips and margins of the individual leaf and with the latter the chlorotic areas do not characteristically show necrotic areas, and if they are present they are large and are not at the tips and margins of the leaf. In the case of potassium hunger the plant is of a bluish-green color, save in the mottled areas between the veins, which have a yellowish cast, while, owing to the necrotic spots drying up, the plants have a rusty appearance, the leaves cupping under as a result of the rim-bound condition caused by the dead tissue at the tip and margins of the leaf around which the living portions attempt to grow but are distorted by dead tissue. A contrast to this is evident in plants suffering from a shortage of magnesium, which are of a normal green save in the chlorotic areas between the principal veins, which are light green to almost white in color. In this instance the leaves turn up or cup up at the tips and margins. If either element is withheld the veins tend to retain their green color. In extreme cases where either element is deficient the veins of the leaves become shriveled and allow the leaves to hang down against the stalk. The stalks are slender and in extreme cases show lesions just below or around the points of attachment of the leaves. The roots resemble each other in that they have few branches and a slimy appearance, but they are yellowish when potassium is deficient and colorless when magnesium hunger is pronounced.

The second group may be subdivided into those elements, such as iron, manganese, and sulphur, the shortage of which does not cause the death of the terminal bud but induces chlorotic effects on the young leaves, and those, such as calcium and boron, which cause the death of the terminal bud and the preceding characteristic symptoms. Where the death of the terminal bud does not take place, distinguishing chlorotic effects appear on the young leaves. A deficiency of iron or manganese is apparent as a chlorosis of the younger leaves, but the veins tend to retain their green color, in contrast to their behavior when there is a deficiency of sulphur, when the veins become lighter green than the tissue between the veins. Iron chlorosis appears as a loss of the green color between the veins with the principal veins tending to retain the green color, but in some cases the entire leaf may be white although typically no necrotic spots are evident. In the case of manganese chlorosis the minutest veins tend to retain their green color, thus giving a checkered appearance to the leaf. In no instance have perfectly white leaves been seen. The leaves also typically show small necrotic spots distributed over the leaf surface. The stalk is short and slender in all cases of decided deficiency. The roots differ in appearance, those of plants suffering from iron hunger being of a brown color and showing many short branches on a relatively short primary root; those of a plant suffering from sulphur hunger being white and characteristically abundant and much branched, while those of a plant showing manganese hunger are not especially characteristic save that they are not quite so abundant.

Those effects classed under the second group having as their final result the death of the terminal bud, which progresses in characteristic

steps, include calcium and boron deficiency symptoms. The effects of the former are to be distinguished from those of the latter by a peculiar hooking of the young leaves making up the bud, where about one-third of the leaf from the tip hooks sharply downward. This is followed by the death of the tips and margins of these young leaves so that in later growth the tips and margins are missing or have a cut-out appearance. The first sign of boron deficiency, on the contrary, is a light-green color of the bud leaves characteristically at the base of the individual leaf, where decomposition takes place to some extent. When the decomposition does not involve all the tissue and later growth takes place, these leaves are distorted at the base by the growth around the injured areas. If the breakdown of the tissue at the base of the young leaf is complete the tip may remain alive and green for some time. The final result is the death of the terminal bud from calcium or boron hunger. If calcium is lacking, such plants take on an abnormally dark-green color in contrast to the unhealthy light-green color of plants affected by a lack of boron. The leaves of plants lacking boron become glabrous, stiff, and brittle. The stalk and roots do not show any especially distinct contrasting characteristics. The stalks die back in both cases, and the roots are short and much branched and of a dirty-brown color, indicating more or less decomposition.

The foregoing effects are typically illustrated in Plate 1. A key for quickly identifying these effects is as follows:

KEY TO DEFICIENCY EFFECTS ON TOBACCO PLANTS GROWN IN SOLUTION CULTURES [5]

Decreased growth; more or less localized effects; causal parasites absent.

- Group 1.—Effects general on whole plant or localized on older or lower leaves of plant.
  - General, on whole plant; also yellowing and drying up or firing of lower leaves.
    - **Nitrogen**: Plant light green. Lower leaves yellow and dry to a light-brown color. Stalk slender and short. Roots long, with few lateral branches, white in color.
    - **Phosphorus**: Plant dark green. Lower leaves may yellow and dry to a greenish-brown to black color. Stalk slender and short. Roots long with few lateral branches, reddish-brown color.
  - Local, occurring as mottling or chlorosis, with or without necrotic spotting of lower leaves; little or no drying up of lower leaves.
    - **Potassium**: Lower leaves mottled with necrotic spots at tips and margins, which are tucked or cupped under. Stalk slender, necrotic areas in extreme cases. Roots long, with few lateral branches and of a yellowish, slimy appearance.
    - **Magnesium**: Lower leaves chlorotic and typically show no spots. Tips and margins turned or cupped upward. Stalk slender, necrotic areas in extreme cases. Roots long, with few lateral branches and slimy in appearance.
- Group 2.—Effects localized on newer or bud leaves of plant.
  - Terminal bud remains alive, chlorosis of newer or bud leaves, with or without necrotic spots; veins light or dark green.
    - **Iron**: Young leaves chlorotic, typically show no spots. Principal veins typically green. Stalk slender and short. Roots short, with abundant short laterals, brown in color.
    - **Manganese**: Young leaves chlorotic, with necrotic spots scattered over leaf. Smallest veins tend to remain green, producing a checkered effect on leaf. Stalk slender. Roots not abundant; brownish in color.
    - **Sulphur**: Young leaves light green; no necrotic spots. Veins lighter green than intervein tissue. Stalk short and slender. Roots white, abundant, and much branched.
  - Death of terminal bud, which is preceded by peculiar distortions at the tips or base of young leaves making up bud.
    - **Calcium**: Young leaves making up terminal bud first typically hooked, then die back at tips and margins so that later growth of such leaves shows a cut-out appearance at tips and margins. Stalk finally dies back at terminal bud. Roots short, much branched, dark brown in color, more or less decomposed.
    - **Boron**: Young leaves making up terminal bud first light green at base, then more or less breakdown takes place at base of young leaf, and if later growth follows, leaf shows twisted growth. Stalk finally dies back at terminal bud. Roots have many short laterals, brown color, and somewhat decomposed.

[5] Symptoms under these conditions are similar to those observed in the field on the tobacco plant, except for iron and manganese deficiency, which have not been seen on tobacco in the field.

GENERAL CONSIDERATIONS

The characteristic effects, since they are growth phenomena, produced by the deficiency of the various essential elements are modified to a certain extent by other conditions affecting growth, particularly the unfavorable light conditions prevailing at this latitude in midwinter. It is to be recognized also that growth manifestations are altered to some extent by conditions prevailing in the greenhouse but that basically the characteristic symptoms will be found to be essentially the same.

It is often difficult to determine whether the effect on growth produced as a result of the shortage of a certain element comes about because the element is needed for certain metabolic processes or because it antagonizes some other element. In some instances both forces seem to be in operation; but whether such is the case or not is an academic question which will not be considered in this bulletin. The initial effects produced when an element is withheld are, as a rule, the ones that are most typical and serve best to distinguish one deficiency from another.

It is well to call attention here to the fact that the evidence given in Tables 2 to 7 and the curves presented in the various figures show that plants are much slower in manifesting deficiency effects when an element is removed than they are in showing recovery when the element is supplied. This result may be considered as a buffer effect of the plant which enables it to survive under unfavorable environments. Such a condition is particularly favorable from a practical point of view because through this response the plant is enabled to take advantage of favorable conditions rapidly and is slow in responding to unfavorable conditions of nutrient supply.

A point that may be mentioned here is the effect on growth when more than one of the essential elements are lacking. While not a great deal of work has been conducted in the possibility of combining these effects, it appears from the limited studies made that the effect of the absence of one of the lacking elements usually dominates, and the effects of the other missing elements are largely masked. When two or more elements are withheld there may be more dwarfing than where only one is deficient, yet the outstanding symptoms will be only those of one element. For example, when there is a boron deficiency it dominates all other deficiencies, and while the symptoms shown by the plant may be slightly modified they are essentially those of boron deficiency.

SUMMARY

The distinctive deficiency effects of N, P, K, Mg, Ca, B, S, Fe, and Mn on the tobacco plant, as produced in a series of nutrient solutions so devised as to make possible the withholding of each essential element as desired without changing the amounts of other elements present, are described and illustrated. A reduction in growth results when any essential element is withheld, but on close examination typical symptoms which serve to distinguish the deficient elements are evident on the root, stem, or leaf or on the plant as a whole.

Typically a deficiency of nitrogen is shown by the plant as a whole assuming a light-green color, with more or less yellowing and drying or firing of the lower leaves to a light-brown color. The roots are long, little branched, and white. A shortage of phosphorus, on the

contrary, produces a plant that is dark green in color and may show some yellowing and drying of the lower leaves to a greenish-brown color. The roots of such plants are long, little branched, and reddish brown in color, owing to the presence of iron compounds on their surface.

Potassium and magnesium hunger, in contrast to nitrogen and phosphorus hunger, show localized effects, of which chlorosis of the lower leaves is the dominant characteristic. Typical potassium hunger is distinguished from magnesium hunger by the small necrotic spots or specks at the tip and margins of the chlorotic leaves which usually do not occur in the case of the latter. The chlorotic areas in the case of potassium hunger are of a yellowish color, while with magnesium hunger they are pale green or white, with the principal veins tending to retain the green color in both cases. The leaves turn or tuck under at the tips and margins with potassium deficiency and tend to turn or cup up in the case of magnesium hunger.

As contrasted with the deficiencies given above, which are general or become apparent on the older or lower leaves, those showing themselves typically on the new growth or bud leaves are iron, manganese, sulphur, calcium, and boron. Deficiency of iron, manganese, or sulphur does not result in the death of the terminal bud, while lack of calcium or boron produces death of the terminal bud as the final result. The first three deficiencies produce chlorosis of the younger leaves, each of a characteristic type. Iron chlorosis and manganese chlorosis resemble each other in that the veins tend to retain their green color, but in the case of manganese deficiency a necrotic spotting occurs scattered over the leaf, while no necrotic spots occur with iron deficiency. The chlorosis resulting from sulphur deficiency differs from that just described in that the veins are of a lighter green color than the tissue between the veins. In the case of sulphur hunger the roots are typical, being unusually abundant and white in color, while with iron and manganese shortage they are not so abundant nor so white.

Calcium and boron deficiencies differ from each other in that the initial effects of their shortage produce different symptoms. A shortage of calcium first becomes apparent as a peculiar hooking downward of the tip of the young leaves of the bud, followed by the death of the young leaves at their tips and margins, and if later growth takes place the tips and margins show a cut-out appearance. In contrast with this effect, a shortage of boron is shown in a light-green color at the base of the young leaves of the bud, followed by their breakdown which, if not too severe, is followed by later growth, which causes the young leaves to become distorted or twisted at their bases. In most cases of boron deficiency the tip of the leaf remains alive for some time after the base has broken down.

The foregoing contrasts have served as a basis for the construction of a key which may help in quickly identifying by comparison the contrasting effects of the deficiencies of each of the essential elements studied. All the described deficiency effects are relatively slower in developing than is the recovery of the plant when the elements are supplied.

LITERATURE CITED

(1) GARNER, W. W., MCMURTREY, J. E., JR., BACON, C. W., and MOSS, E. G.
1923. SAND DROWN, A CHLOROSIS OF TOBACCO DUE TO MAGNESIUM DEFICIENCY, AND THE RELATION OF SULPHATES AND CHLORIDS OF POTASSIUM TO THE DISEASE. Jour. Agr. Research 23:27–40, illus.

(2) ——— MCMURTREY, J. E., JR., BOWLING, J. D., JR., and MOSS, E. G.
1930. MAGNESIUM AND CALCIUM REQUIREMENTS OF THE TOBACCO CROP. Jour. Agr. Research 40:145–168, illus.

(3) ——— MCMURTREY, J. E., JR., BOWLING, J. D., and MOSS, E. G.
1930. RÔLE OF CHLORINE IN NUTRITION AND GROWTH OF THE TOBACCO PLANT AND ITS EFFECT ON THE QUALITY OF THE CURED LEAF. Jour. Agr. Research 40:627–648, illus.

(4) ——— MCMURTREY, J. E., JR., and MOSS, E. G.
1922. SAND DROWN, A CHLOROSIS OF TOBACCO AND OTHER PLANTS RESULTING FROM MAGNESIUM DEFICIENCY. Science (n. s.) 56:341–342.

(5) GERICKE, W. F.
1925. SALT REQUIREMENTS OF WHEAT PLANTS AT DIFFERENT GROWTH PHASES. Bot. Gaz. 80:410–425, illus.

(6) GINSBURG, J. M.
1925. COMPOSITION AND APPEARANCE OF SOYBEAN PLANTS GROWN IN CULTURE SOLUTIONS EACH LACKING A DIFFERENT ESSENTIAL ELEMENT. Soil Sci. 20:1–13, illus.

(7) GRIS, E.
1847. ADDITION À UNE PRÉCÉDENTE NOTE CONCERNANT DES EXPÉRIENCES SUR L'APPLICATION DES SELS DE FER À LA VÉGÉTATION, ET SPÉCIALEMENT AU TRAITEMENT DES PLANTES CHLOROSÉES, LANGUISSANTES ET MENACÉES D'UNE MORT PROCHAINE. Compt. Rend. Acad. Sci. [Paris] 25:276–278.

(8) MCMURTREY, J. E., JR.
1929. THE EFFECT OF BORON DEFICIENCY ON THE GROWTH OF TOBACCO PLANTS IN AERATED AND UNAERATED SOLUTIONS. Jour. Agr. Research 38:371–380, illus.

(9) MAZÉ, P.
1914. RECHERCHES DE PHYSIOLOGIE VÉGÉTALE (QUATRIÉME MÉMOIRE). INFLUENCES RESPECTIVES DES ÉLÉMENTS DE LA SOLUTION MINÉRALE SUR LE DEVELOPPEMENT DU MAÏS. Ann. Inst. Pasteur 28:[21]–68, illus.

(10) ———.
1919. RECHERCHE D'UNE SOLUTION PUREMENT MINÉRALE CAPABLE D'ASSURER L'ÉVOLUTION COMPLÈTE DU MAÏS CULTIVÉ A L'ABRI DES MICROBES. Ann. Inst. Pasteur 33:[139]–1743, illus.

(11) MOSS, E. G., MCMURTREY, J. E., JR., LUNN, W. M., and CARR, J. M.
1927. FERTILIZER TESTS WITH FLUE-CURED TOBACCO. U. S. Dept. Agr. Tech. Bul. 12, 59 p., illus.

(12) RUSSELL, SIR E. J.
1927. SOIL CONDITIONS AND PLANT GROWTH. Ed. 5, 516 p., illus. London, New York [etc.]

(13) SALM-HORSTMAR, PRINCE DE
1849. VERSUCHE ÜBER DIE NOTHWENDIGEN ASCHENBESTANDTHEILE EINER PFLANZEN-SPECIES. Jour. Prakt. Chem. 46:[193]–211.

(14) ———
1851. RECHERCHES SUR LA NUTRITION DE L'AVOINE, PARTICULIÈREMENT EN CE QUI CONCERNE LES MATIÈRES INORGANIQUES QUI SONT NÉCESSAIRES À CETTE NUTRITION. Translated from German by Barral and Laverrière. Ann. Chim. et Phys. (3) 32:461–508.

(15) VALLEAU, W. D., and JOHNSON, E. M.
1927. TOBACCO FRENCHING—A NITROGEN DEFICIENCY DISEASE. Ky. Agr. Expt. Sta. Bul. 281, p. [179]–253, illus.

(16) WILFARTH, H., and WIMMER, G.
1902. DIE WIRKUNG DES KALIUMS AUF DAS PFLANZENLEBEN NACH VEGETATIONS-VERSUCHEN MIT KARTOFFELN, TABAK, BUCHWEIZEN, SENF, ZICHORIEN UND HAFER. Arb. Deut. Landw. Gesell. 68, 106 p., illus.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Tobacco and Plant Nutrition	W. W. GARNER, *Principal Physiologist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE 1933

TECHNICAL BULLETIN NO. 339 JANUARY, 1933

SOME RESULTS OF INBREEDING GRADE GUERNSEY AND GRADE HOLSTEIN-FRIESIAN CATTLE

BY

T. E. WOODWARD
Senior Dairy Husbandman

AND

R. R. GRAVES
Chief, Division of Dairy Cattle Breeding, Feeding, and Management
Bureau of Dairy Industry

UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - - - - - - Price 15 cents

TECHNICAL BULLETIN NO. 339 JANUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

SOME RESULTS OF INBREEDING GRADE GUERNSEY AND GRADE HOLSTEIN-FRIESIAN CATTLE

By T. E. WOODWARD, *Senior Dairy Husbandman*, and R. R. GRAVES, *Chief, Division of Dairy Cattle Breeding, Feeding, and Management, Bureau of Dairy Industry*

CONTENTS

	Page
Purpose, plan, and progress of the investigation	1
Effects of inbreeding grade Guernseys	3
Birth weight of calves	4
Normality of calves at birth	4
Mature weight of cows	5
Production of milk and butterfat	6
Color markings	8
Effects of inbreeding grade Holsteins	8
Breeding of bulls used	8
Breeding of foundation cows	9
Effects of inbreeding grade Holsteins—Con.	
Services required for conception	9
Gestation and normality of calves	9
Birth weight of calves	10
Mortality of calves	20
Rate of growth of calves	20
Mature weight of cows	22
The vigor of cows	23
Production of milk and butterfat	20
Color markings	33
Summary	30

PURPOSE, PLAN, AND PROGRESS OF THE INVESTIGATION

The original purpose of this investigation in inbreeding grade cattle was to determine whether a good dairy herd could be bred up from an ordinary one by the use of only one good bull. The plan was to mate all the female offspring with their own sire throughout his entire useful life. The investigation was started in 1912 at the United States Dairy Experiment Station at Beltsville, Md. In that year 16 cows of mixed breeding and of only average production were purchased for the experiment. The appearance of these cows indicated the presence of Shorthorn, Angus, Hereford, and Jersey breeding. A well-bred Guernsey bull, Imp. Prince Billy of Rich Neck 17799, was purchased to mate with them. In the next year 11 grade Jersey cows, which were somewhat higher producers than the cows in the original purchase, were added to the herd; and at about the same time a registered Holstein-Friesian bull, Johan Woodcrest Lad 11th 103987, was purchased. Inasmuch as the results of such a breeding experiment would depend largely upon the individuality of the bull used, it was thought best to have two bulls of different breeds and to mate some of the cows with one bull and some with the other; but in each case to mate the female offspring with their own sire for successive generations.

The investigation proceeded substantially as planned until the herd became infected with infectious abortion. This disease appeared in 1914, and in 1918 had become so severe that an effort was made to check it by disposing of the affected animals. The disease,

coupled with the efforts to eradicate it, nearly terminated the experiment. The females of the Guernsey group were breeding with such uncertainty that it was decided to discontinue the work with that breed. Enough females of the Holstein group were salvaged to warrant continuing the experiment with this breed.

When the Holstein sire, Johan Woodcrest Lad 11th, became impotent, a fair start had already been made in the inbreeding of grade Holsteins. As no injurious results from the practice were yet apparent, it was decided to continue close inbreeding for the purpose of determining its effects upon the health, size, and production of the cattle. The second sire used in the Holstein group was an 87.5 per cent inbred son of the first sire, Johan Woodcrest Lad 11th. The third sire was a 75 per cent inbred son of the second sire. The fourth sire was the result of mating the third sire back to his own dam, and he is still in service. The plan has been to select for service those bulls most intensely inbred.

As used in this publication, the terms "50 per cent daughter of a bull," and "50 per cent son of a bull," mean the offspring obtained when the bull is mated with a cow that is either unrelated or only distantly related to him. A 75 per cent daughter or son of a bull is the result of mating the bull with one of his 50 per cent daughters, and an 87.5 per cent daughter or son of a bull is the result of mating him with one of his 75 per cent daughters.

The offspring of unrelated parents are referred to as "outbred" animals, and the offspring of parents so closely related as a sire and daughter or brother and sister are referred to as "inbred."

Most of the cows with which the second Holstein sire was mated were 50 per cent outbred daughters and 75 per cent inbred daughters of the first Holstein sire, while the second sire himself was an 87.5 per cent inbred son of the first sire. For this reason the terms 50 and 75 per cent, as applied to the daughters of the second sire that were out of his half-sisters, fail to express the full extent of the inbreeding.

The results of this investigation are measured by: (1) Birth weight and normality of calves; (2) weight at maturity; and (3) production of milk and butterfat. For the experiment with Holstein sires additional data are presented on the number of services required for conception, the growth and vigor of calves, and the vigor of cows.

In order to bring all this information to a comparable basis, it was necessary to use certain correction factors: (1) To make the birth weights of grade Holstein calves from immature dams comparable to those of calves from mature dams, 4 pounds was added to the birth weight of each of the calves from 2-year-old dams. (2) To make the birth weights of the bull calves comparable to those of the heifer calves (the number of calves was insufficient to justify a study of each sex), 7 pounds was deducted from the birth weight of each of the bull calves.

These correction factors were determined from data collected in this experiment, and were found to be the same as those obtained in the study conducted by this bureau at its Huntley, Mont., Experiment Station,[1] on factors influencing variation in weight of dairy cows and calves.

[1] MOSELEY, T. W., STUART, D., and GRAVES, R. R. DAIRY WORK AT THE HUNTLEY FIELD STATION, HUNTLEY, MONT., 1913–1927. U. S. Dept. Agr. Tech. Bul. 116: 24–29. 1929.

Sufficient data from which to prepare similar correction factors for the grade Guernseys were not obtainable. The correction factors for this breed were adapted from those used for the Holsteins by assuming figures approximately proportional to the birth weights of the calves of the two breeds. Three instead of 4 pounds was added to the birth weight of calves from 2-year-old dams, and 5 instead of 7 pounds was deducted from the birth weight of bull calves.

The average body weights of the cows during lactation were determined by averaging weights taken 3, 4, and 5 months after calving if the cow was under official-test conditions, or 6, 7, and 8 months after calving if she was in the general herd. These weights were intended to represent a period when the cows were in good milking condition, but before they were heavy with calf. As the cows under official-test conditions were fed more liberally than those in the general herd, they gained in weight more rapidly after calving, and it was necessary to take their weights earlier in the stage of lactation than those of the cows kept in the general herd. In figuring the weights of young cows to maturity, the following age-correction factors prepared from records obtained in this investigation were used:

For cows 2 to 3 years old multiply the weight by 1.20
For cows 3 to 4 years old multiply the weight by 1.11
For cows 4 to 5 years old multiply the weight by 1.06
For cows 5 to 6 years old multiply the weight by 1.02

Most of the production records in this investigation were made either with immature cows or with cows kept under herd conditions rather than under official-test conditions. If was necessary, therefore, to correct the production records for both of these factors. All of the grade Guernseys and some of the grade Holsteins, as well as the foundation stock from which they sprang, were kept under herd conditions. In figuring to maturity the production records of all these animals kept under herd conditions the age-correction figures of Clark [2] for Holsteins and Guernseys were used. In correcting for age, the production records of grade Holsteins kept under test conditions, unpublished figures prepared in the Bureau of Dairy Industry were used. The age-correction factors applied for such cows when exactly 2, 3, 4, 5, and 6 years old at time of calving were: 1.40, 1.21, 1.10, 1.04, and 1.00, respectively, with monthly gradations for intermediate ages.

In addition to correcting the production records for age, it was also necessary, as just stated, to convert those records made under herd conditions to an equivalent of those made under official-test conditions. In a previous investigation,[3] it was found that cows kept under the official-test conditions used at the Beltsville station, gave 50 per cent more milk and butterfat than they did when kept under ordinary herd conditions. Therefore, the herd records given herein, after being corrected for age of cow, were converted to the equivalent of test records by applying the factor 1.50.

EFFECTS OF INBREEDING GRADE GUERNSEYS

The Guernsey bull Imp. Prince Billy of Rich Neck 17799, used in this work, was by Billy's France of the Isle 21183, and out of Froome's

[2] CLARK, R. S. THE CORRELATION BETWEEN CHANGES IN AGE AND MILK PRODUCTION OF DAIRY COWS UNDER OTHER THAN OFFICIAL TESTING CONDITIONS. Jour. Dairy Sci. 7:552. 1924.

[3] WOODWARD, T. E. INFLUENCE OF TWO PLANES OF FEEDING AND CARE UPON MILK PRODUCTION. Jour. Dairy Sci. 10:283-291. 1927.

Queen 28706, a cow with an advanced registry record of 13,902 pounds of milk and 716 pounds of butterfat. A photograph of this bull is shown in Plate 1 (in pocket) along with those of five foundation cows, their daughters and granddaughters.

BIRTH WEIGHT OF CALVES

The average birth weight of the 50 per cent daughters of the Guernsey bull, and the average birth weight of his 75 per cent calves from these 50 per cent daughters are presented in Table 1. Also, the average birth weight of three of his 75 per cent daughters is compared with the average birth weight of his 87.5 per cent calves out of these three daughters.

TABLE 1.—*Average birth weights of 75 and 87.5 per cent calves [1] compared with the average birth weights of their dams, all by the Guernsey bull*

Description of calves	Calves	Average birth weight	Description of dams	Dams	Average birth weight	Calf and dam comparisons
	Number	*Pounds*		*Number*	*Pounds*	*Number*
75 per cent	22	65.8	50 per cent daughters [2]	12	69.9	22
87.5 per cent	3	61.0	75 per cent daughters	3	63.7	3

[1] Corrected for age of dam and sex of calf.
[2] Birth weights of dams of these daughters unknown.

Table 1 shows that there was a small but consistent decline in the birth weight of the calves in this group as the inbreeding became more intense. Another matter, however, must be considered in interpreting these data. Of the twelve 50 per cent daughters in this table, eight were out of dams of indiscriminate breeding. It may be possible that these eight dams had some "large-breed" ancestry and carried an inheritance for greater weight at birth than that carried by the Guernsey bull, in which case it would be expected that mating them with this bull for successive generations would decrease the average birth weight of the calves. On the other hand, the four remaining 50 per cent daughters were out of grade Jersey cows, which no doubt carried an inheritance for smaller calves at birth than that carried by the Guernsey bull. These four grade Jersey daughters had an average birth weight of 70 pounds and gave birth to eight 75 per cent calves with an average birth weight of 61.6 pounds. Two of these 75 per cent daughters had an average birth weight of 63 pounds, and gave birth to two 87.5 per cent calves with an average birth weight of 61 pounds. Therefore, inbreeding decreased the birth weights of the offspring from the four grade Jerseys, although the use of the Guernsey bull probably would normally tend toward heavier calves.

NORMALITY OF CALVES AT BIRTH

A number of deformed calves resulted from mating the Guernsey bull to his daughters. Table 2 shows the total number of calves sired by this bull, and the number of normal calves, abortions, deformed and dead calves, and normal still-born calves, from the foundation cows and from his 50 per cent daughters out of these foundation cows.

TABLE 2.—*Reproduction record of cows mated with the Guernsey bull*

Description of dams	Cows mated	Recorded calvings	Normal calves	Abortions	Calves deformed and dead	Calves normal in conformation but dead
Foundation cows	21	57	51	6	0	0
50 per cent daughters of Guernsey bull	23	48	22	19	6	1

The large increase in number of abortions by the 50 per cent daughters as compared with the foundation cows can be attributed partly, if not wholly, to the prevalence of infectious abortion in the herd.

All the deformed calves either were dead at birth or died within a few hours. The anatomical abnormalities of a typical deformed calf are described by the veterinarian in charge of the herd, as follows:

> This specimen showed a compound curvature of the spine. The bodies of dorsal vertebræ were compressed laterally, resulting in a lateral curvature. The bodies of lumbar vertebræ showed anterior compression, resulting in posterior curvature. The lateral processes and spinous processes were modified somewhat in conformity to the changed positions which they assumed as a result of the modification of the body formation. The intravertebral foramina were lessened in diameter upon concavity of the curvatures which would have resulted in an impingement upon the nerves issuing from the spinal cord through them. The long bones of both anterior and posterior limbs showed marked curvatures with the convexities laterally away from the median line. The humerus and femur of each limb were abnormally shortened. The extremities of these long bones were enlarged. The skull showed a general shortening and widening with a permanent bulging of the frontal bones.

This description agrees closely with the appearance of deformed calves examined by Wriedt,[4] who states that "these calves had greatly foreshortened heads and upper jawbone, and stumpy, crooked legs which could not support the animal's weight." Wriedt concludes that this type of deformity is caused by a double dose of a Mendelian recessive factor.

It is probable that none of the foundation cows in the herd at Beltsville carried this recessive factor. In that case, approximately one-half of the daughters by Prince Billy of Rich Neck and out of the foundation cows would receive this factor from their sire. When this bull was bred back to his own daughters, the normal expectancy would be that approximately one-eighth of his inbred calves would receive the factor that causes this type of deformity, both from their sire and their dams, and would be deformed. Table 2 shows that out of 48 inbred calves by Prince Billy of Rich Neck 6 were deformed. This is the number that was to be expected according to the Mendelian ratio, where this deformity is caused by a double dose of a recessive factor, and confirms Wriedt's findings and observations.

MATURE WEIGHT OF COWS

The 12 foundation cows produced 18 daughters for which body weights are available. The average weight of the foundation cows was 934 pounds, and that of the 18 daughters was 1,077 pounds. In order to make a better comparison of the weights of foundation

[4] WRIEDT, C., HEREDITY IN LIVE STOCK. p. 72. London. 1930.

cows, 50 per cent daughters, and 75 per cent daughters, Table 3 was prepared, including only those foundation cows having both daughters and granddaughters.

TABLE 3.—*Weights of five foundation cows, and of their daughters and granddaughters by the Guernsey bull*

Item	Cows	Average weight
	Number	*Pounds*
Foundation cows	5	993
Daughters [1]	5	1,131
Granddaughters [2]	6	956

[1] 50 per cent daughters of the Guernsey bull.
[2] 75 per cent daughters of the Guernsey bull.

As the foundation cattle were from an average farm herd, it is not unlikely that conditions under which they were raised made them smaller than they would have been if raised under more favorable conditions of feeding and management. The average weight of five foundation cows of mixed breeding (993 pounds) is a little less than the average weight of Guernsey cows. For these reasons the increase in weight shown by the 50 per cent daughters of the bull over their dams was to be expected. Every one of the six 75 per cent daughters of the Guernsey bull, however, was smaller than her dam. The average weight of these six 75 per cent daughters was 175 pounds less than the average weight of their dams, which were 50 per cent daughters of the Guernsey bull. This large decline can not be explained on any grounds other than the effects of inbreeding.

PRODUCTION OF MILK AND BUTTERFAT

All production records given in this report were made under ordinary herd conditions. If a cow had more than one lactation record, the one that was highest when figured to maturity was used. The records were either for complete lactation periods or for the first 365 days of prolonged lactations. The records of 12 foundation cows and of their daughters by the Guernsey bull are compared in Table 4, and a comparision of the records of 5 foundation cows with those of 50 per cent daughters and of 75 per cent daughters of this bull is shown in Table 5.

TABLE 4.—*Milk and butterfat records of foundation cows and of the 50 per cent daughters of the Guernsey bull*

Foundation cows					50 per cent daughters				Increase (+) or decrease (−) of daughters over dams		
Cow No.	Predominating blood	Milk	Butterfat		Cow No.	Milk	Butterfat		Milk	Butterfat	
		Pounds	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*	*Pounds*	*Per cent*	*Pounds*
1	Shorthorn	3,770	4.11	155	33	6,378	4.78	305	+2,608	+0.67	+150
1	do	3,770	4.11	155	41	4,693	5.60	263	+923	+1.49	+108
1	do	3,770	4.11	155	56	5,016	4.67	234	+1,246	+.56	+79
2	Jersey	8,184	4.73	387	40	744	4.70	35	−7,440	−.03	−352
5	Shorthorn	6,004	3.43	206	54	9,929	3.86	383	+3,925	+.43	+177
8	Guernsey	6,085	4.22	257	39	5,319	5.32	283	−766	+1.10	+26
8	do	6,085	4.22	257	66	5,297	5.25	278	−788	+1.03	+21
9	Shorthorn	5,501	4.11	226	52	6,120	4.75	291	+619	+.64	+65
12	Jersey	5,749	4.21	242	43	6,021	4.58	276	+272	+.37	+34
12	do	5,749	4.21	242	57	[1] 6,650	4.62	307	+901	+.41	+65
14	Shorthorn	6,064	4.90	297	48	7,895	4.41	348	+1,831	−.49	+51
14	do	6,064	4.90	297	61	6,610	5.17	342	+546	+.27	+45
17	Jersey	6,877	5.16	355	44	5,888	4.60	271	−989	−.56	−84
17	do	6,877	5.16	355	60	6,744	5.34	360	−133	+.18	+5
17	do	6,877	5.16	355	84	7,740	4.78	370	+863	−.38	+15
21	do	10,431	4.56	476	58	5,840	4.90	286	−4,591	+.34	−190
21	do	10,431	4.56	476	71	7,535	4.38	330	−2,896	−.18	−146
24	do	8,224	4.17	343	47	8,302	4.81	399	+78	+.64	+56
24	do	8,224	4.17	343	81	5,399	4.70	254	−2,825	+.53	−89
27	do	6,672	4.09	273	49	8,069	4.56	368	+1,397	+.47	+95
32	Holstein	9,549	4.43	423	53	7,035	4.65	327	−2,514	+.22	−96
Average		6,712	[2] 4.45	299		6,344	[2] 4.74	300			
Difference in averages									−368	+.29	+1
Average, omitting No. 2 and her daughter		6,639	4.43	294		6,324	[2] 4.74	314			
Difference in averages									−15	+.31	+20

[1] Estimated from a 6-month record.

[2] Percentage based on the averages.

TABLE 5.—*Milk and butterfat records of five foundation cows and of the 50 per cent daughters and 75 per cent daughters of the Guernsey bull*

Foundation cows				50 per cent daughters				75 per cent daughters			
Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat	
	Pounds	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*
1	3,770	4.11	155	33	6,378	4.78	305	90	5,887	5.61	330
5	6,004	3.43	206	54	9,929	3.86	383	99	7,364	4.66	343
12	5,749	4.21	242	57	6,650	4.62	307	89	7,053	5.47	386
21	10,431	4.56	476	71	7,535	4.38	330	95	5,597	4.56	255
24	8,224	4.17	343	81	5,399	4.70	254	93	8,877	4.60	408
Average	6,836	[1] 4.16	284		7,178	[1] 4.40	316		6,953	[1] 4.95	344

[1] Percentage based on the averages.

Although 15 of the 21 daughters of the foundation cows produced more butterfat than their dams, the average increase was only 1 pound. One peculiar individual, cow 40 (Table 4) had much to do with bringing down the average of the daughters. As this cow was apparently in perfect health there appeared to be no justification for excluding her record. If the record of this cow and that of her dam were omitted, the average production of milk by the daughters would be about the same as that by the dams and the increase in butterfat would be 20 pounds.

These tables show that the successive matings with the Guernsey bull lowered the production of milk and increased the percentage of butterfat, resulting in a small increase in total butterfat. Three of the five 75 per cent daughters produced more butterfat than their dams; the average increase over their dams was 28 pounds.

In percentage of butterfat the five foundation cows ranged from 3.43 to 4.56 per cent, a difference of 1.13 per cent. (Table 5.) The outbred daughters ranged from 3.86 to 4.78 per cent, a difference of 0.92 per cent. Both the low and the high percentages were increased. The inbred daughters ranged in percentage of butterfat from 4.56 to 5.61, a difference of 1.05 per cent. Both the low and the high percentages were markedly increased. It appears that this sire was able to raise the level of the butterfat test in his outbred daughters and, through the concentration of his inheritance, to raise it still further in his inbred daughters, although the variability was not greatly decreased. The average percentage of butterfat for the five foundation dams was 4.16, the average for their five outbred daughters was 4.40, and the average for the five inbred daughters was 4.95 per cent.

COLOR MARKINGS

The Mendelian behavior of spotting is illustrated in the color patterns of the daughters of this Guernsey sire from cows of broken and solid color. Cow 1, in Plate 1, was a grade roan Shorthorn. The roan color was eliminated in one cross. All the foundation cows of solid color had offspring of solid color in the first generation and all but one of the inbred cows that descended from foundation cows of solid color were of solid color. It is known that spotting is recessive to solid color. Apparently these foundation cows were pure in their inheritance for the factors determining solid color, and, therefore, could not transmit the inheritance for spotting to any of the first-generation heifers; and since the inheritance for solid color is dominant, these first-generation daughters would be of solid color regardless of whether they received an inheritance for spotting from their sire. On the other hand, this sire carried very little white for a Guernsey. Except for some white on the belly and on one leg he was of solid color. Ordinarily it would be expected that more of the inbred daughters would be spotted but it is entirely possible for the spotting to crop out in only one of this limited number of inbred daughters, even if the sire is transmitting spotting to all his offspring. That he did transmit the character for broken color is shown by the fact that both his outbred and inbred daughters from the spotted foundation cow 23 are broken colored.

EFFECTS OF INBREEDING GRADE HOLSTEINS

BREEDING OF BULLS USED

The first Holstein bull used in this work, sire 1, Johan Woodcrest Lad 11th 103987, was by Johan Woodcrest Lad 52145 and out of Lillian Walker Nudine 16229, a cow with an advanced-registry record of 16,229 pounds of milk and 518 pounds of butterfat at the age of 2 years and 4 months.

The second bull used, sire 2, was an 87.5 per cent son of sire 1. Photographs of sire 1 and sire 2 appear in the illustrated pedigree of sire 2 shown in Plate 2. (In pocket.)

The third bull used, sire 3 (pl. 3, in pocket), was a 75 per cent son of sire 2. Sire 3 died of bloat at the age of 2 years and 3 months.

The fourth bull, sire 4, now in service, is the result of mating sire 3 with his own dam.

BREEDING OF FOUNDATION COWS

The immediate ancestry of the first eight cows listed below is unknown. The opinion on their breeding is based upon their appearance. The next six cows were by sires of known breeding.

Cow No.	Breeding	Cow No.	Breeding
7	Jersey-Shorthorn.	29	Grade Holstein.
18	Grade Jersey.	33	Grade Guernsey.
20	Do.	34	Grade Jersey.
21	Do.	84	Do.
23	Do.	93	75 per cent inbred Guernsey.
25	Do.		
A–6	Grade Holstein.	A–13	Grade Holstein.
A–7	Do.		

Photographs of these cows along with those of their offspring by sire 1 and sire 2 are shown in Plates 4 and 5. (In pocket.)

SERVICES REQUIRED FOR CONCEPTION

Complete service records of the animals in this experiment have been kept for a number of years. The average number of services per conception for the animals of varying degrees of inbreeding for the period from January 1, 1923, to July 1, 1930, is given in Table 6.

TABLE 6.—*Services required for conception by cows with different intensities of inbreeding*

Intensity of inbreeding	Cows served	Average services per conception
Cows served by sire 2, an 87.5 per cent son of sire 1:		
50 per cent daughters of sire 1	6	[1] 4.4
75 per cent daughters of sire 1	5	2.6
87.5 per cent daughter of sire 1	1	1.3
Cows served by sire 2 or sire 3, the latter being a 75 per cent son of sire 2:		
Cows unrelated to these sires	6	2.8
50 per cent daughters of sire 2	19	2.7
75 per cent daughters of sire 2	9	2.4

[1] If the record of 1 cow served 14 times were omitted the average would be 2.4.

Table 6 shows that the inbreeding of these cows did not adversely affect the readiness with which they conceived; in general, the average number of services per conception decreased slightly as the intensity of inbreeding increased. Compared with the other cows at the Beltsville station, the cows in this experiment required fewer services per conception.

GESTATION AND NORMALITY OF CALVES

Since January 1, 1926, more complete gestation and calving records than formerly have been kept. In the period from that date to March 14, 1931, 104 calves in this experiment were born. Of these 89 were inbred and 15 outbred. All the outbred calves were normal in every way. Of the inbred calves, however, 4 were carried full time but were born dead, 1 fetus was mummified, and 3 were abor-

tions (not infectious). Thus 9 per cent of the gestations in which inbreeding was a factor terminated abnormally.

Comparable figures for 126 outbred registered Holstein calves in the general herd are: 112 normal, 9 carried full gestation period but born dead, 2 mummified fetuses, and 3 abortions (not infectious), or 11 per cent of the gestations terminated abnormally.

If the results from the grade herd only are considered, inbreeding appears detrimental. On the other hand, if the inbred grades are compared with the outbred registered Holsteins, little difference in the efficiency of breeding as regards gestation and normalcy of calves is found.

Only one deformed inbred calf has been produced. This was some years previous to the period stated above. The calf was the result of mating sire 1 with one of his 50 per cent daughters. The posterior part of the spinal column, including the tail, was missing and the calf was dead at birth. The deformity was entirely unlike the "bulldog" calves described in the discussion of the inbred Guernseys. As there was only one deformed calf, and as it was less intensely inbred than many of the calves born subsequently, it does not seem reasonable to attribute this one case to inbreeding.

BIRTH WEIGHT OF CALVES

The intensity of inbreeding and the average birth weights of the calves are shown in Table 7. The birth weights of only three of the foundation cows are known.

TABLE 7.—*Birth weights of grade Holstein calves, outbred and of various degrees of inbreeding*

Group	Calves	Dams	Calf and dam comparisons	Average birth weight	
				Calves	Dams
	BY SIRE 1		*Number*	*Pounds*	*Pounds*
A	50 per cent calves (outbred)	Foundation cows	4	84	71
B	75 per cent calves (inbred)	50 per cent daughters of sire 1 (outbred)	21	85	82
C	87.5 per cent calves (inbred)	75 per cent daughters of sire 1 (inbred)	3	86	68
	BY SIRE 2 [1]				
D	50 per cent calves (outbred)	Cows unrelated to sire 2	10	87	69
D 1	75 per cent calves (inbred)	50 per cent daughters of sire 2 (outbred) (see D).	9	80	87
E	50 per cent calves (inbred)	50 per cent daughters of sire 1 (outbred)	15	93	82
E 1	75 per cent calves (inbred)	Daughters of sire 2 from outbred daughters of sire 1 (see E).	8	86	103
F	50 per cent calves (inbred)	75 per cent daughters of sire 1 (inbred)	12	79	82
F 1	75 per cent calves (inbred)	Daughters of sire 2 from inbred daughters of sire 1 (see F).	8	71	85
G	50 per cent calves (inbred)	87.5 per cent daughter of sire 1 (inbred)	4	75	93
	BY SIRE 3 [2]				
H	50 per cent calves (inbred)	3 daughters of sire 1; 14 daughters of sire 2.	17	68	87

[1] An 87.5 per cent son of sire 1.

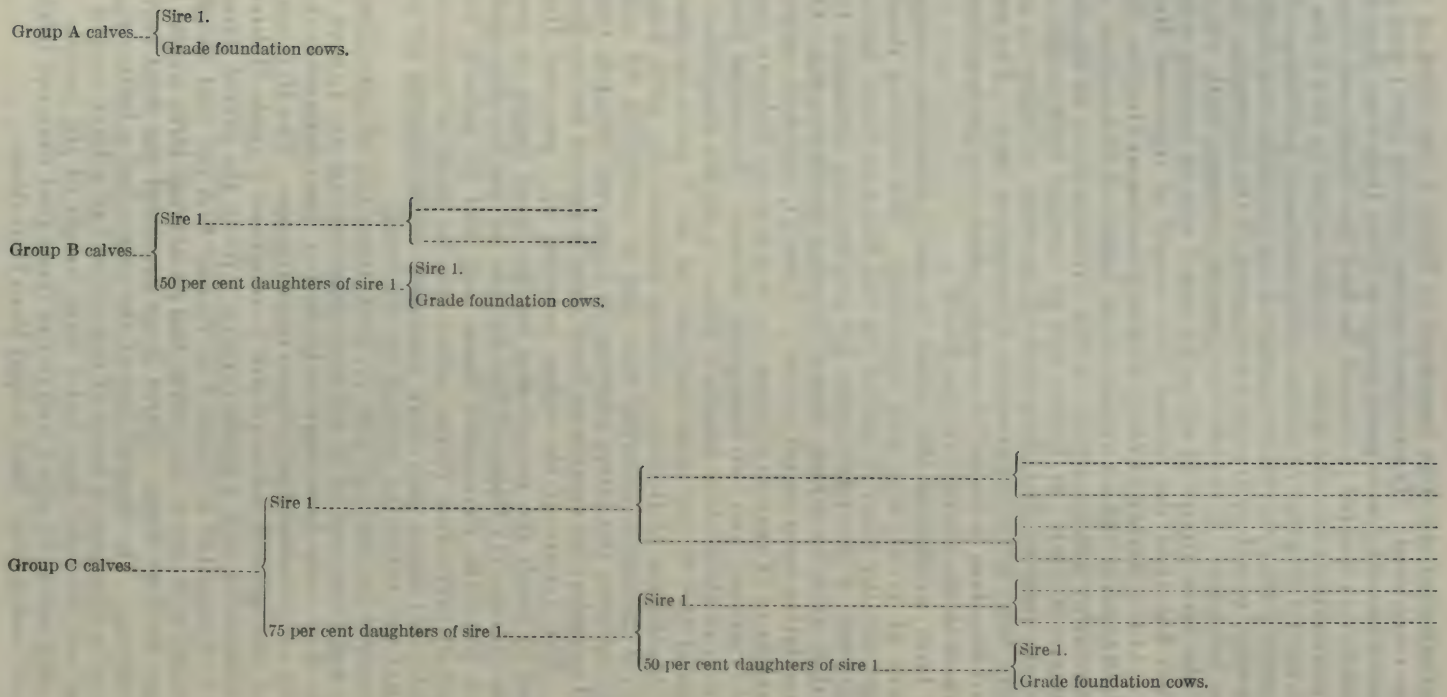
[2] A 75 per cent son of sire 2.

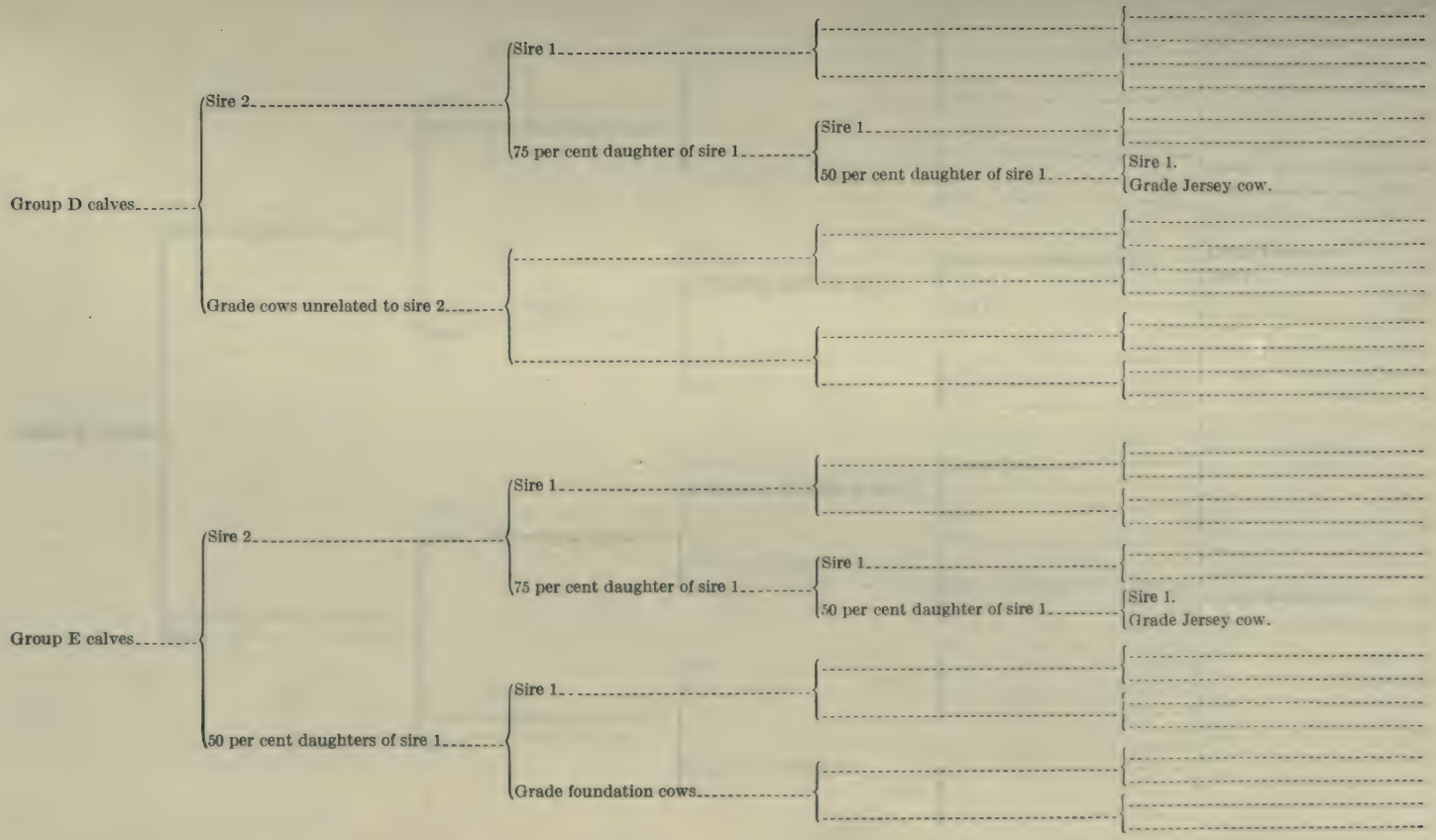
Because of the difficulty of showing clearly the breeding of the calves shown in Table 7, the diagrams in pedigree form have been prepared for each group of calves. (See pages 12 to 18.) The group designation on the left side of each pedigree corresponds to the similar group designation of the calves shown in Table 7.

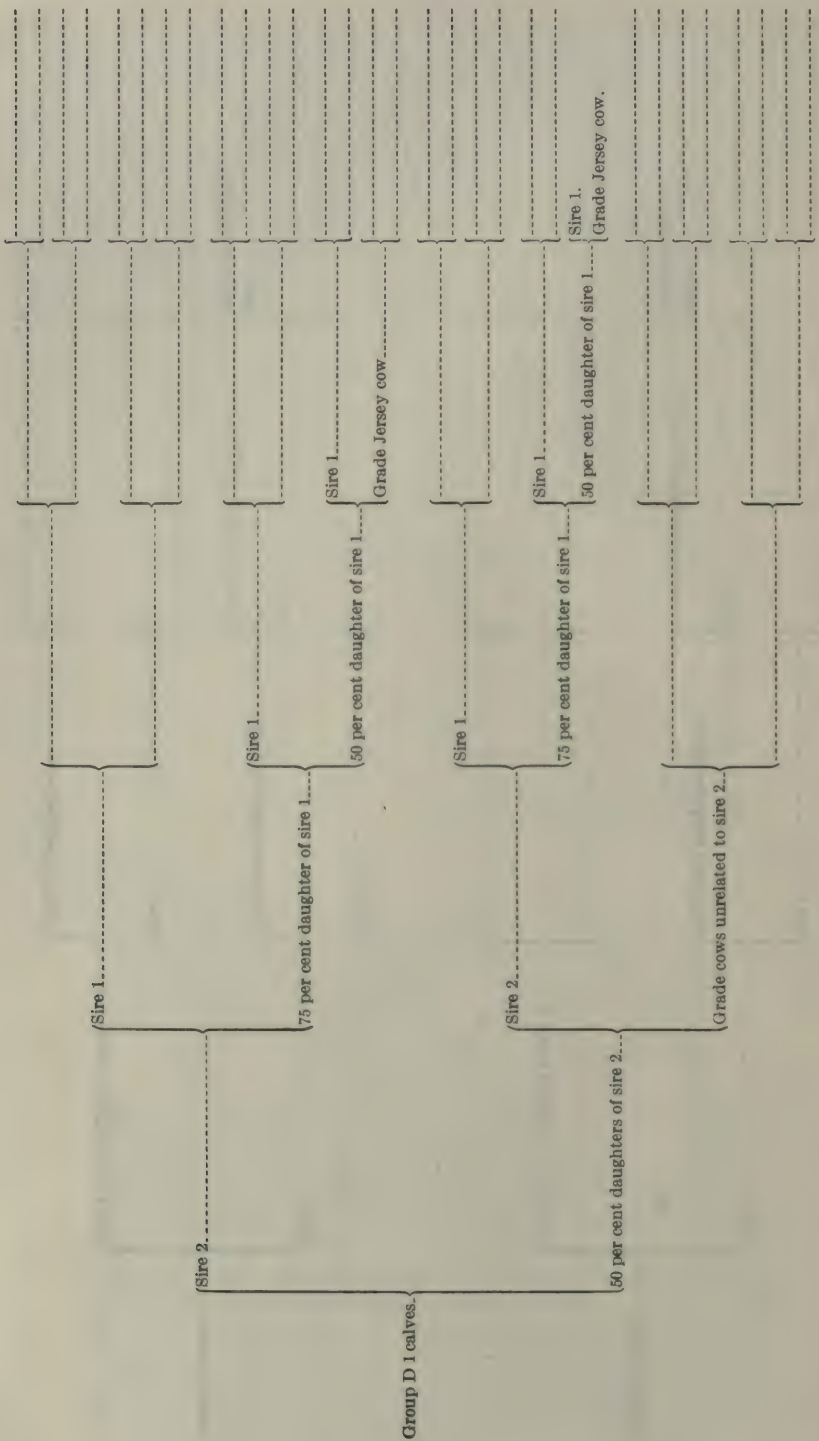
In interpreting the data presented in Table 7 the effect of breed must be considered. The outbred calves both by sire 1 and sire 2 of Holstein breeding were much larger at birth than were their dams. This was to be expected in view of the fact that Jersey and Guernsey blood predominated in the dams. In the calves by sire 1 the birth weights show a progressive increase with increase in percentage of Holstein breeding from successive matings of sire 1 with his own daughters. This is what would ordinarily be expected if the inbreeding had no adverse influence. However, the greatest average birth weight of any of the three groups of calves by sire 1 was 86 pounds, which is somewhat less than the normal birth weight of registered Holstein calves. At the Bureau of Dairy Industry station at Huntley, Mont., 79 Holstein calves had an average birth weight of 92.5 pounds (using the same correction factors as in this investigation); at the station at Ardmore, S. Dak., 17 heifers had an average birth weight of 90 pounds, the same as 23 heifers at the University of Missouri; and at Beltsville, Md., 27 heifers averaged 97 pounds at birth. The average for the 146 calves is about 93 pounds, which may be considered as fairly close to the average for the breed.

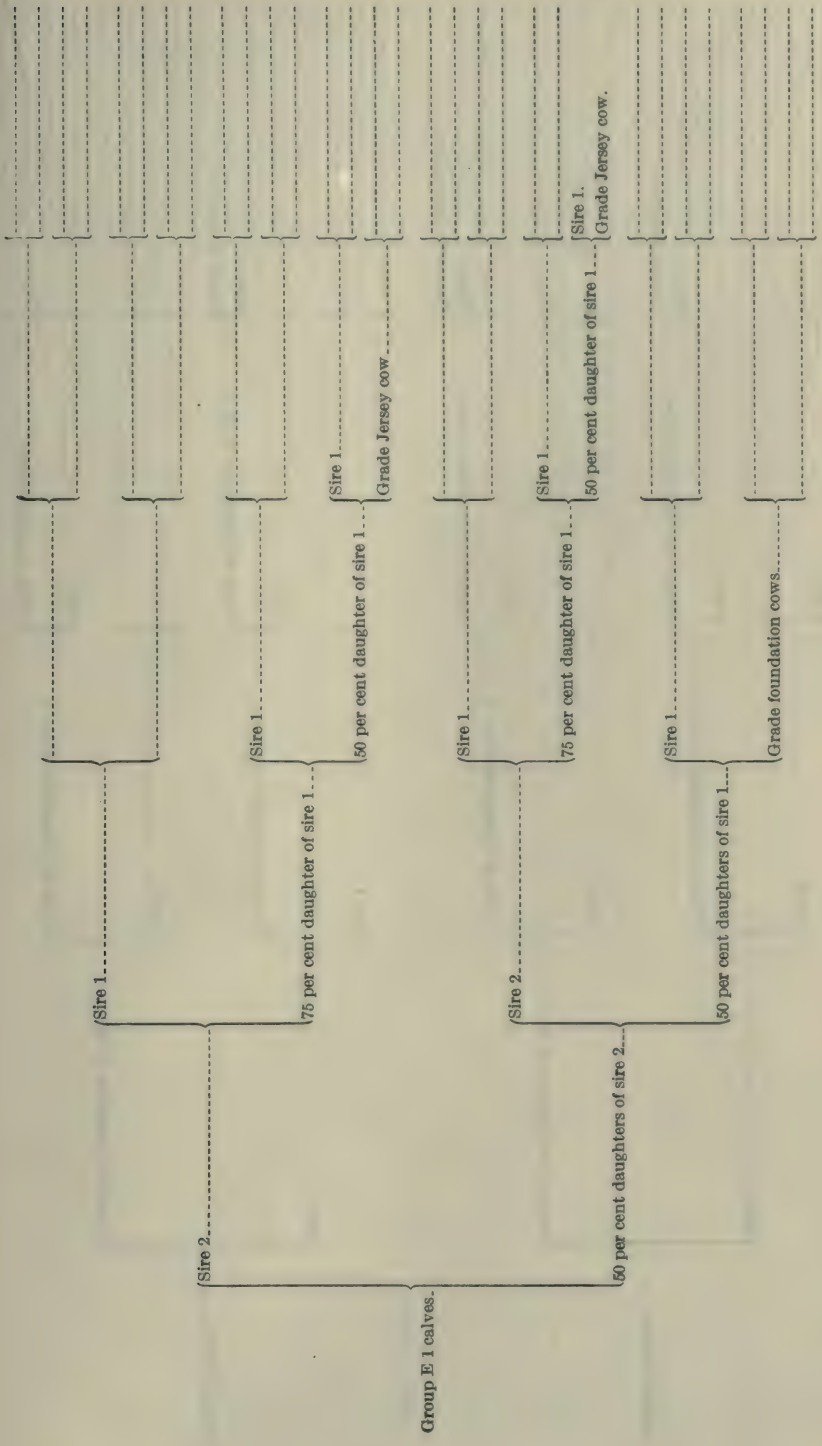
The birth weights of the calves by sire 1 show the contrasting influences of breed, size, and inbreeding. The outbred daughters are much smaller than is normal for the Holstein breed because of the influence of the inheritance for smaller size possessed by the foundation dams in which Jersey breeding predominated. Of the four foundation cows mated to sire 1 (Table 7), for which an average birth weight of 71 pounds is given, one was a grade Holstein, one was a grade Guernsey, and two were grade Jerseys. Somewhat the same proportion of these three breeds is found in all the foundation cows or dams of the 50 per cent daughters of sire 1 given in group B. As the percentage of Holstein breeding increases the birth weight of the calves increases, showing that size is controlled by multiple factors, but even the calves carrying 87.5 per cent Holstein breeding are still considerably smaller at birth than is normal for the Holstein breed. This failure of the calves carrying 87.5 per cent Holstein breeding to reach the normal size for the breed might be ascribed to three things: (1) Some of the factors for smaller size that were received from the foundation dams may still be present; (2) the influence of inbreeding (these calves are the result of three crosses to sire 1); (3) sire 1 may have possessed an inheritance for size at birth that was below the average for the breed.

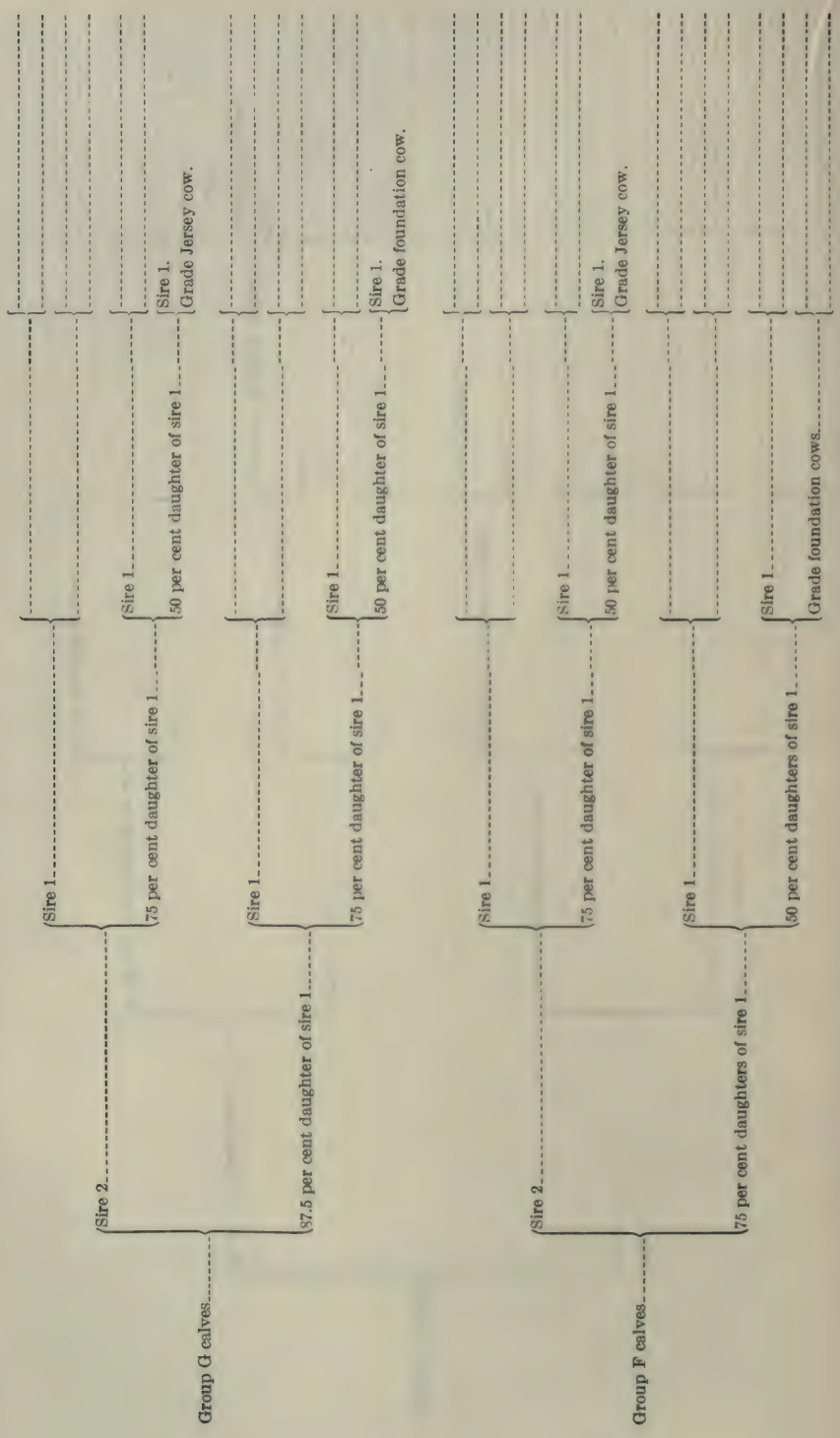
The calves by sire 2 (Table 7), both those out of cows unrelated to him and those out of 50 per cent daughters of sire 1, were larger at birth than their dams were at birth, but this relationship did not hold true as the inbreeding became more intense. The 10 foundation dams of the outbred calves of sire 2 comprised 3 grade Holsteins, 3 grade Guernseys, and 4 grade Jerseys. When the inbred daughters of sire 1, designated in Table 7 as 75 and 87.5 per cent daughters, were mated with sire 2, the calves had an average birth weight lower that that of their dams. Three dams produced the eight calves in the E1 group. The dam of four of the calves had a birth weight of 107 pounds, the dam of three of the calves had a birth weight of 98 pounds, and the third dam had a birth weight of 105 pounds. The 75 per cent calves by sire 2 and out of dams that were not related to sire 1 also had a lower birth weight than their dams.

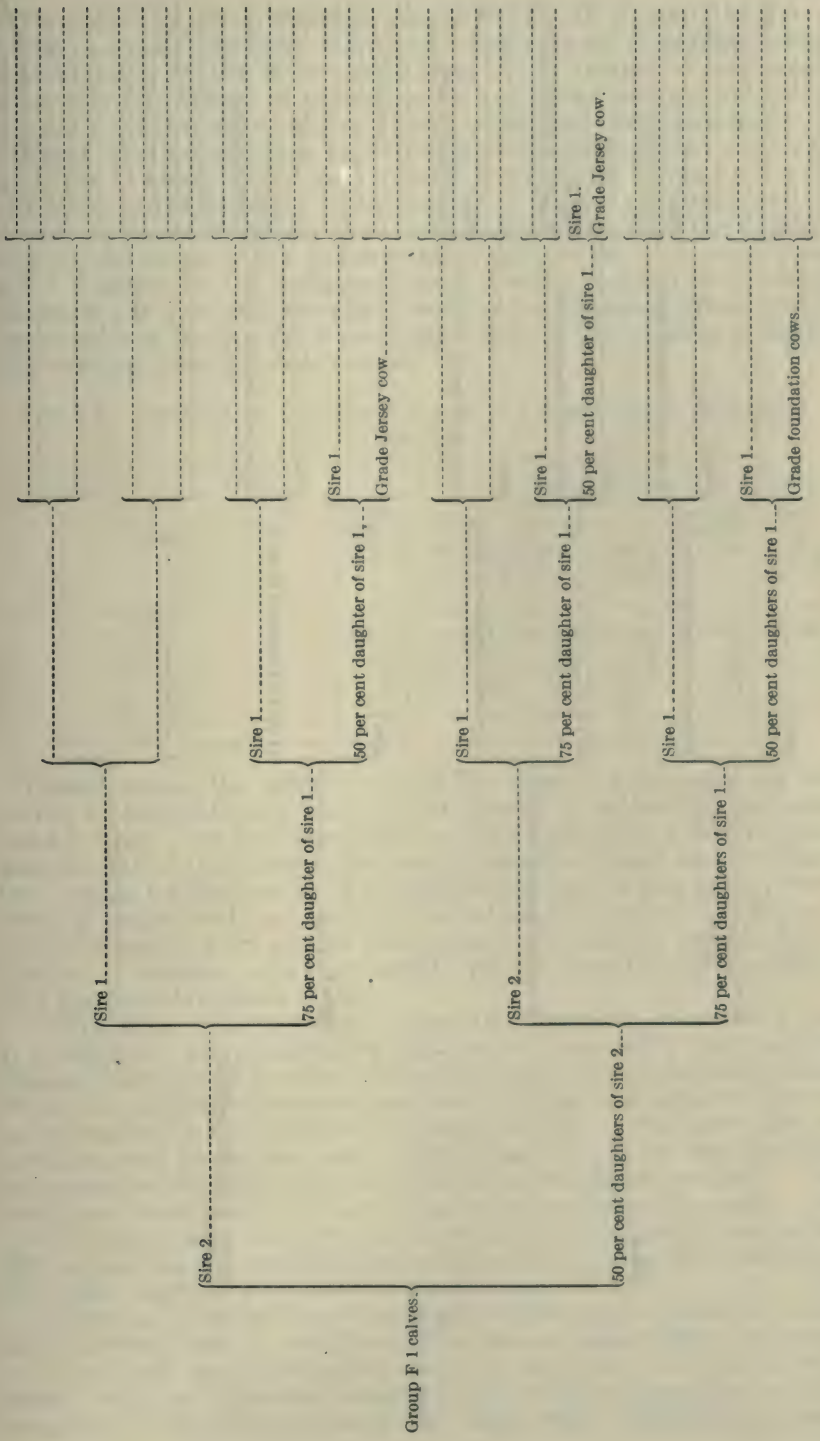

Group A calves
Sire 1.
Grade foundation cows.
Group B calves
Sire 1
50 per cent daughters of sire 1
Sire 1.
Grade foundation cows.
Group C calves
Sire 1
75 per cent daughters of sire 1
Sire 1
50 per cent daughters of sire 1
Sire 1.
Grade foundation cows.

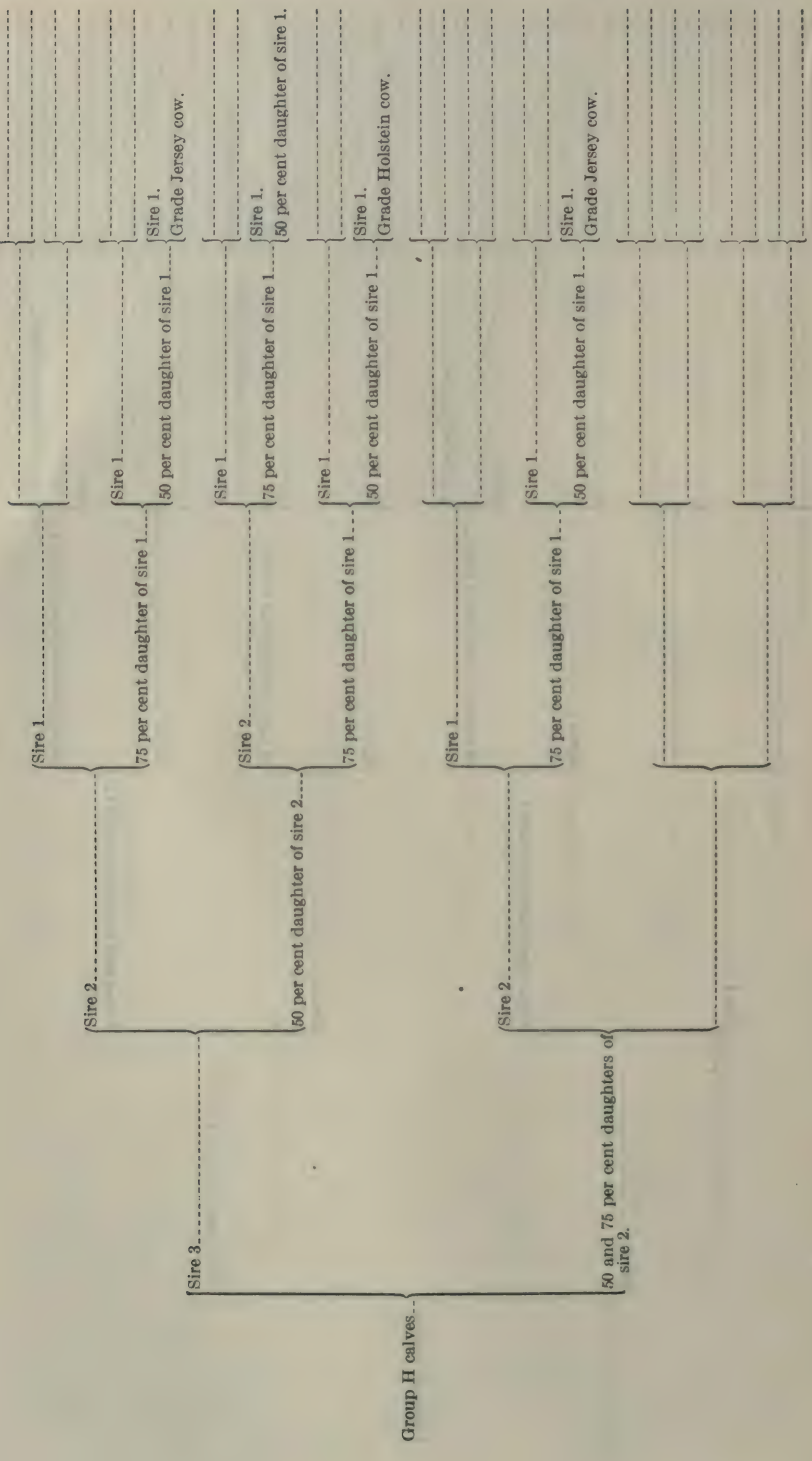

Group D calves
Sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
Grade cows unrelated to sire 2
Group E calves
Sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
50 per cent daughters of sire 1
Sire 1
Grade foundation cows


Group D 1 calves.
Sire 2.
50 per cent daughters of sire 2.
Sire 1.
75 per cent daughter of sire 1.
Sire 1
50 per cent daughter of sire 1.
Grade Jersey cow
Sire 2.
Grade cows unrelated to sire 2.
Sire 1
75 per cent daughter of sire 1.
Sire 1
50 per cent daughter of sire 1.
Sire 1.
Grade Jersey cow.


Group E 1 calves.
Sire 2
50 per cent daughters of sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Grade Jersey cow
Sire 2
50 per cent daughters of sire 1
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
Sire 1
50 per cent daughters of sire 1
Sire 1
Grade foundation cows.


Group G calves
Sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
87.5 per cent daughter of sire 1
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade foundation cow.
Group F calves
Sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
75 per cent daughters of sire 1
Sire 1
50 per cent daughters of sire 1
Sire 1
Grade foundation cows.


Group F 1 calves.
Sire 2
50 per cent daughters of sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Grade Jersey cow
Sire 2
75 per cent daughters of sire 1
Sire 1
75 per cent daughter of sire 1
Sire 1
50 per cent daughter of sire 1
Grade Jersey cow.
Sire 1
75 per cent daughters of sire 1
Sire 1
50 per cent daughters of sire 1
Grade foundation cows


Group H calves
Sire 3
50 and 75 per cent daughters of sire 2.
Sire 2
50 per cent daughter of sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
Sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1.
50 per cent daughter of sire 1.
Sire 1
50 per cent daughter of sire 1
Sire 1.
Grade Holstein cow.
Sire 2
Sire 1
75 per cent daughter of sire 1
Sire 1.
Grade Jersey cow.
Sire 1
50 per cent daughter of sire 1

The calves by sire 2, shown in groups F1, E1, G, F, and E in Table 7, are the most intensely inbred, the intensity of inbreeding being approximately in the order given here. It is impossible to present accurately the degree of inbreeding in any group because the grade foundation dams may appear in the sire's and dam's ancestry a different number of times for different individuals within a group. In Table 8, which shows the variation in weight of calves by sire 2, according to the intensity of inbreeding, is shown the coefficient of inbreeding as calculated by the Wright method based on the appearance of the sires in the pedigree alone; the number of times that sire 1 appears in the pedigree (sire 1 being the individual whose inheritance is most concentrated), and the percentage of grade breeding remaining on the sire's and dam's side of the average pedigree representing these different groups.

TABLE 8.—*Variation in weight of calves by sire 2 according to intensity of inbreeding*

Group	Wright's coefficient of inbreeding	Times sire 1 appears	Grade breeding remaining on—		Average weight of calves	Average weight more (+) or less (−) than that of dams
			Sire's side of pedigree	Dam's side of pedigree		
	Per cent	*Number*	*Per cent*	*Per cent*	*Pounds*	*Pounds*
F1	50.8	8	12.5	18.75	71	−14
E1	45.3	7	12.5	31.25	86	−17
G	40.3	6	12.5	12.5	75	−18
F	32.8	5	12.5	25	79	−3
E	21.9	4	12.5	50	93	+11

Except among the calves in group E1, there is a tendency for the calves to be smaller at birth as the degree of inbreeding becomes more intense. As has been explained the eight calves in E1 group were all out of three dams who were themselves larger at birth than the average for the breed. The decline in weight in this group, however, is second only to that of the calves in group G. The four calves in group G are all out of the same dam and her average birth weight, 93 pounds, was considerably higher than that of the other 87.5 per cent daughters of sire 1.

The decrease in birth weight of the calves by sire 3, shown in Table 7, is marked. Of 17 calves by this sire not one had a birth weight greater than that of its dam. Whether a part of this decrease might be due to an inherent character of sire 3 to beget small calves can not be determined definitely from the data available. There is evidence, however, that he can sire calves of good size; in the one case in which he was mated with an unrelated cow, the calf weighed 98 pounds. The same cow when mated with sire 2 had a calf weighing 97 pounds. It would appear that the very low average birth weight of his calves (68 pounds), as compared to that of their dams (87 pounds) as shown in Table 7, must be attributed to inbreeding.

Additional data on two cows, each mated with a different bull, tend to strengthen the conclusion that intense inbreeding may result in lower birth weight of calves. Cow A–26, shown in Plate 4, was mated with an unrelated registered Holstein bull and had a calf weighing 90 pounds; the same cow when mated with her own sire

(sire 2 of this experiment) had a calf weighing 72 pounds; and when she was mated with her son, by the same sire, the resulting calf weighed 63 pounds. Cow 94, shown in Plate 4, a 75 per cent daughter of sire 1, was mated twice with sire 1 and produced two calves with an average weight of 82 pounds; the same cow when mated with her son by the same sire produced three calves with an average weight of 76 pounds.

MORTALITY OF CALVES

Of the 54 normal female calves born in the Holstein group of this experiment in the 10 years ended January 1, 1931, 41 were inbred and 13 outbred. All the outbred calves lived for a year or more but 5 of the inbred calves died. One died of navel infection, 1 of pneumonia, and 3 of pneumonia with complications. Of the 89 outbred registered Holsteins born in the Beltsville experimental herd during the same period, only 2 died before reaching the age of 1 year. One died of pneumonia, the other of digestive troubles.

As all the grade calves that died were inbred and as the percentage of mortalities was somewhat greater with the inbred grades than with the outbred registered Holsteins, the indications are that the inbred calves lacked the vitality of the outbred calves. However, some consideration should be given to the fact that three of the five deaths among the grades occurred during an epidemic of pneumonia; that the number of inbred calves was relatively large at the time; and that one death was the result of navel infection.

RATE OF GROWTH OF CALVES

Table 9 shows the weights, at various ages, of daughters of sire 1 and sire 2, and certain dam-and-daughter comparisons are included for sire 2. This table also gives the weights of registered Holstein calves at Beltsville and other stations.

TABLE 9.—*Weights of outbred and inbred daughters of sires 1 and 2 and of calves from other herds at various ages up to 2 years*

Group	Breeding or herd	Animals	Average weight at age of—			
			3 months	6 months	12 months	24 months
	DAUGHTERS OF SIRE 1					
		Number	*Pounds*	*Pounds*	*Pounds*	*Pounds*
A	50 per cent daughters (outbred)	4	169	321	576	921
B	75 per cent daughters (inbred)	[1] 6	157	307	541	938
C	87.5 per cent daughter (inbred)	1	173	327	616	.....
	DAUGHTERS OF SIRE 2[2] AND THEIR DAMS					
D	50 per cent daughters (outbred)	9	195	355	636	[3] 1,034
D1	75 per cent daughters (inbred)	3	201	371	625	[4] 1,011
.....	Dams, Group D cows (outbred)	3	190	363	628	[4] 1,062
E	50 per cent daughters (inbred)	4	193	356	610	1,042
E1	75 per cent daughters (inbred)	2	189	333	615	993
.....	Dams, Group E cows (inbred)	2	190	351	580	1,089
F	50 per cent daughters (inbred)	5	160	320	565	974
.....	Dams, 75 per cent daughters of sire 1 (inbred)	4	155	312	562	943
F1	75 per cent daughters (inbred)	2	171	313	575	997
.....	Dams, group F cows (inbred)	2	168	331	556	982

[1] 2 of 6 calves were fed a milk substitute.
[2] An 87.5 per cent son of sire 1.
[3] 8 animals for 24 months age.
[4] 2 animals for 24 months age.

TABLE 9.—*Weights of outbred and inbred daughters of sires 1 and 2 and of calves from other herds at various ages up to 2 years*—Continued

REGISTERED OUTBRED HOLSTEIN-FRIESIAN CALVES FROM OTHER HERDS [5]

Group	Breeding or herd	Animals	Average weight at age of—			
			3 months	6 months	12 months	24 months
		Number	*Pounds*	*Pounds*	*Pounds*	*Pounds*
	Beltsville, Md.	27	197	360	627	1,056
	Huntley, Mont.	16	230	425	721	1,071
	Ardmore, S. Dak.	17	238	403	590	973
	University of Missouri	23	200	349	558	841

[5] From U. S. Dept. Agr. Tech. Bul. 116. (See footnote 1, p. 2.)

With the daughters of sire 1 there has been no apparent slackening of the rate of growth as a result of inbreeding. This statement also applies to the daughters of sire 2, if limited to dam-and-daughter comparisons. However, if the nine outbred daughters of sire 2 out of dams unrelated to him are taken as the basis of comparison, the more closely inbred calves were in general smaller than the outbred calves at the different ages given in Table 9. These inbred grade heifers are in fact not so much smaller than the registered heifers at the Beltsville station at 2 years of age as they were at birth. The calves in F1 group were 26.8 per cent smaller at birth, while the two animals that have reached 2 years of age are only 5.6 per cent smaller at that age than the average of the registered heifers. The calves in the E1 group were 11.3 per cent smaller at birth and the two animals that have reached 2 years of age were only 6 per cent smaller than the average 2-year-old registered heifer. The calves in the F group were 18.6 per cent smaller at birth and only 7.8 per cent smaller at 2 years of age. These data may be somewhat misleading because of the small number of the grade heifers on which weights at 2 years of age are available. The rate of feeding of the registered calves and the inbred grade calves at Beltsville was the same.

Other evidence that inbreeding is affecting the rate of growth is shown in Table 10. During a short period during which sire 2 was not in active service some of the inbred cows were mated with unrelated, registered Holstein bulls. Cows A–26 and A–36 gave birth to heifer calves A–55 and A–54, respectively. These two outbred heifers exceeded their inbred dams in birth weight and rate of growth. At 2 years of age they averaged 161 pounds more than their dams at the same age. All the individual weights of inbred heifers used in preparing the average weights in Table 9 were smaller than those of these two outbred heifers.

TABLE 10.—*Weights of outbred heifers and their inbred dams at various ages up to 2 years*

Breeding and cow No.	At birth	3 months	6 months	12 months	24 months
Outbred heifers:	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
A–55	90	228	439	760	1,214
A–54	80	208	387	682	1,114
Average	85	218	413	721	1,164
Inbred dams:					
A–26	68	164	343	615	1,052
A–36	78	183	322	608	954
Average	73	173	332	611	1,003

MATURE WEIGHT OF COWS

The effect of intensive inbreeding on the size of the cows at maturity is indicated in Table 11, which presents data on the foundation cows and progeny of the first and second Holstein sires used, arranged as dam-and-daughter comparisons.

TABLE 11.—*Effects of intensive inbreeding on mature weights of cows in the Holstein group*

Group	Daughters	Dams	Daughter-dam comparisons	Average mature weight	
				Daughters	Dams
	Daughters of sire 1:			*Pounds*	*Pounds*
A	50 per cent daughters (outbred)	Foundation cows (outbred)	[1] 11	1,176	944
B	75 per cent daughters (inbred)	50 per cent daughters (outbred)	7	1,144	1,163
C	87.5 per cent daughter (inbred)	75 per cent daughter of sire 1 (inbred)	1	1,220	1,024
	Daughters of sire 2: [2]				
D	50 per cent daughters (outbred)	Cows unrelated to sire 2 (outbred)	[3] 9	1,275	1,049
D 1	75 per cent daughter (inbred)	D cow (outbred)	1	1,226	1,264
E	50 per cent daughters (inbred)	50 per cent daughters of sire 1 (outbred)	4	1,313	1,203
E 1	75 per cent daughter (inbred)	E cow (inbred)	1	1,321	1,274
F	50 per cent daughters (inbred)	75 per cent daughters of sire 1 (inbred)	6	1,191	1,163
F 1	75 per cent daughter (inbred)	F cow (inbred)	1	1,135	1,278

[1] Of these 11 foundation cows, 7 were grade Jerseys, 1 was a grade Holstein, 1 was a grade Guernsey, and 2 were animals of mixed breeding.
[2] An 87.5 per cent son of sire 1.
[3] Of these 9 foundation cows, 4 were grade Guernseys, 3 were grade Holsteins, and 2 were grade Jerseys.

A large increase in weight resulted from the mating both of sire 1 and sire 2 with unrelated cows which were naturally much smaller than cows of the Holstein breed. It might be expected, also, that the next generation of daughters would show a moderate increase in size, provided some factor other than breed did not prevent such an increase. The fact that the body weights do not consistently show a further increase after the first generation indicates that inbreeding may have had a tendency to reduce the size. The dam-and-daughter comparisons show that many of the daughters were heavier than their dams, still, on the whole, there was no material change in body weights after the first generation of mating with unrelated cows. The aver-

age weight of 44 registered Holsteins raised at the Beltsville station was 1,352 pounds. It will be noted that all of the groups in Table 11 averaged considerably less than 1,352 pounds.

THE VIGOR OF COWS

With the exception of one or two cows, the inbred cows of the Holstein group have not been lacking in vigor. Cow A–28, shown in Plate 4, was the product of mating sire 2 back to his dam. She was not only subnormal in size but was also a delicate feeder. Cow 97, the 75 per cent daughter of sire 1, shown in Plate 6 (in pocket) was somewhat undersized and subject to fits. That inbreeding had anything to do with her condition is questionable. When bred back to her own sire she produced a daughter that attained normal size and was otherwise normal. An outbred registered Holstein cow at Beltsville, that is unrelated to cow 97, has presented a parallel condition. It is possible that a double dose of a recessive factor may have been the cause of this condition in both cow 97 and the unrelated registered cow. In that case, however, more of the inbred daughters of sire 2 should have shown this peculiarity.

PRODUCTION OF MILK AND BUTTERFAT

As none of the bulls used in this investigation were proved bulls at the time they were put into service, it was not known whether they had the ability to transmit high production of milk and butterfat to their daughters. A decrease in production of the daughters as compared with their dams, therefore, would not necessarily prove that inbreeding was detrimental unless such decrease was the result of diminished size or vigor. On the other hand, an increase in production would show two things: (1) That the bulls transmitted high production; and (2) that inbreeding did not result in marked diminution of vigor, otherwise the increase in production could not have been manifested.

RECORDS OF THE DAUGHTERS OF SIRE 1

The milk and butterfat records of outbred and inbred daughters of sire 1 and of the foundation cows to which he was mated are given in Table 12. The table is so arranged that the production records of successive generations of females can be followed across the page from left to right. For example, cow 20, one of the foundation cows, is the dam of cow 63, an outbred or 50 per cent daughter of sire 1; cow 63 is the dam of cow 97, an inbred 75 per cent daughter of sire 1, and she in turn is the dam of the inbred cow A–11, an 87.5 per cent daughter of sire 1. Photographs of these four cows are shown in Plate 6.

The use in this experiment of a number of foundation cows in which Jersey and Guernsey blood predominated makes it necessary to consider the effect of inherent breed differences as well as the influence of inbreeding on the milk and butterfat production of successive generations. Of the seven 75 per cent inbred daughters of sire 1 (Table 12), five had granddams in which Jersey breeding predominated and the other two were from a common granddam in which Holstein breeding predominated. There was an average increase in milk yield and an average decrease in percentage of butterfat for both the outbred and the inbred daughters. This would be the result expected from crossing a Holstein sire on grade Jersey cows.

TABLE 12.—*Production records* [1] *of outbred and inbred daughters of sire 1 and their dams*

Foundation cows				Outbred daughters (50 per cent)[2]			Inbred daughters (75 per cent)[2]			Inbred daughters (87.5 per cent)[2]		
Breeding	Cow No.	Milk	Butterfat	Cow No.	Milk	Butterfat	Cow No.	Milk	Butterfat	Cow No.	Milk	Butterfat
		Pounds	*Per cent* / *Pounds*		*Pounds*	*Per cent* / *Pounds*		*Pounds*	*Per cent* / *Pounds*		*Pounds*	*Per cent* / *Pounds*
Grade Jersey	20	6,350	4.23 / 269	63	11,213	3.24 / 363	97	17,033	3.09 / 526	A–11	17,423	3.28 / 571
Do	20	6,350	4.23 / 269	63	11,213	3.24 / 363	94	19,930	3.17 / 632			
Do	18	8,919	5.36 / 478	46	10,196	4.46 / 455	79	9,691	4.44 / 430			
Do	21	15,647	4.56 / 714	91	19,926	3.91 / 779	A–9	15,241	3.52 / 536			
Do	23	9,308	4.17 / 388	82	18,131	3.68 / 667	A–2	19,682	3.49 / 687			
Grade Holstein	29	17,416	4.18 / 728	51	19,072	3.78 / 721	A–3	17,106	3.61 / 618			
Do	29	17,416	4.18 / 728	51	19,072	3.78 / 721	87	17,325	3.66 / 634			
Average		11,629.4	[3] 4.39 / 510.5		15,546.1	[3] 3.73 / 581.3		16,572.5	[3] 3.50 / 580.4		[4] 17,423	[4] 3.28 / [4] 571

[1] All records have been calculated to a mature basis.

[2] All five of the 50 per cent daughters, three of the seven 75 per cent daughters, and the one 87.5 per cent daughter exceeded their dams in milk production. Three 50 per cent daughters, three 75 per cent daughters, and the one 87.5 per cent daughter exceeded their dams in butterfat production. All 50 per cent and 75 per cent daughters were exceeded by their dams in percentage of butterfat. The 87.5 per cent daughter exceeded her dam in percentage of butterfat.

[3] Percentage based on averages.

[4] Average based on the record of 1 cow.

The outbred daughters were still higher in percentage of butterfat than was inherent for their sire, as is shown by the fact that when they were mated back to their own sire their inbred daughters were all lower in percentage of butterfat. While there was an average increase in milk yield in the three groups, that of the 75 per cent daughters was principally due to the very large increase of the two cows, 97 and 94. These were full sisters descended from cow 20, the lowest producer in the herd. Of the seven 75 per cent inbred daughters of sire 1, only three were better than their dams in milk yield and in production of butterfat. The one 87.5 per cent inbred daughter of sire 1 was better than her dam in milk yield, percentage of butterfat, and total production of butterfat. The 75 per cent inbred daughters, with the exception of cow 79, are quite uniform in milk yield. Here, as in the Guernsey inbreeding data, is a clear indication that there are a number of hereditary factors influencing the total yield of milk and the percentage of fat. This is shown by the increase in milk yield of the daughters and granddaughters of grade Jersey foundation cows with each succeeding generation of Holstein inheritance and also a corresponding decrease in the percentage of butterfat. The highest butterfat test among the foundation cows, that of cow 18, was 5.36 per cent. In this case the actual test was evidently an accurate indication of the inheritance for a high percentage of butterfat that she transmitted to her daughter, cow 46. Although the butterfat test of cow 46 is much lower than that of her dam, because of the modifying influence of the hereditary factors that she received from her Holstein sire, her test is still much higher than that of her Holstein half sisters who are out of lower-testing dams. She in turn has passed along some of the factors for a high test that she received from her dam, cow 18, to her own daughter, cow 79. This latter cow, while somewhat lower in test than her dam, is considerably higher in percentage of butterfat than her inbred sisters. The relatively low milk yield of her grade Jersey granddam has also persisted through the two crosses of Holstein inheritance.

The production records of additional outbred daughters of sire 1, which do not have inbred daughters, are compared with those of their dams in Table 13. Their photographs are shown in Plate 5.

TABLE 13.—*Production records of foundation cows and of their 50 per cent daughters [1] by sire 1*

Foundation cows					Outbred daughters (50 per cent)			
Breeding	Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat	
		Pounds	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*
Grade Jersey	7	10,367	4.09	424	50	14,660	3.83	561
Do	7	10,367	4.09	424	64	15,313	3.84	588
Do	23	9,308	4.17	388	45	11,529	4.29	495
Do	25	9,821	4.40	432	67	15,379	3.83	589
Grade Guernsey	33	13,284	4.70	624	A-14	11,733	3.86	453
Grade Jersey	34	7,036	4.76	335	88	16,728	4.30	719
Average		10,031	[2] 4.37	438		14,224	[2] 3.99	568
Average [3] of 11 paired records [4]		10,711	4.42	473		14,898	3.90	581

[1] All records have been calculated to a mature basis.
[2] Percentage based on averages.
[3] Out of 11 paired records, 10 outbred daughters exceeded their dams in milk production, 8 exceeded their dams in butterfat production, and 1 exceeded her dam in percentage of butterfat.
[4] Includes records of the 5 outbred daughters in Table 12.

The coefficients of variability in yield of milk, percentage of butterfat, and total production of butterfat for the three generations of cows in Table 12 are shown in Table 14. The relative degree of variation both in milk yield and butterfat yield is greatest in the foundation cows and least in the inbred daughters. In percentage of butterfat, the relative degree of variation is greatest in the inbred daughters and only a little less in the outbred daughters than in the foundation dams.

TABLE 14.—*Coefficients of variability for the average milk and butterfat records of daughters of sire 1 and their dams*

Group	Coefficient and probable error for—		
	Yield of milk	Percentage of butterfat	Yield of butterfat
Foundation cows	30.40±5.02	8.45±1.21	30.40±5.02
50 per cent outbred daughters of sire 1	21.61±3.11	8.25±1.19	21.58±3.10
75 and 87.5 per cent inbred daughters of sire 1	17.96±3.03	11.13±1.88	13.09±2.21

Sire 1 had five registered daughters with production records made in the Beltsville, Md., and Huntley, Mont., experiment station herds. These records are given in Table 15 for comparison with the records of his inbred grade daughters, especially for percentage of butterfat.

TABLE 15.—*Production records of five registered daughters of sire 1*

Cow No.	Age		Milk	Butterfat	
	Yrs.	*Mos.*	*Pounds*	*Per cent*	*Pounds*
216	4	1	15,946	3.24	518
222	4	7	13,317	3.42	456
212	4	2	8,855	3.70	[1] 328
214 [2]	2	2	17,843	3.05	546
	5	7	16,308	3.36	548
220	2	8	16,593	3.36	559
Average			14,204	3.39	482

[1] Herd test.
[2] Only the mature record of cow 214 included in the average.

The average of 3.39 per cent of butterfat for these five registered daughters of sire 1, as compared to 3.50 per cent for his inbred grade daughters, apparently indicates that the latter show some influence of their higher-testing granddams.

From the summarized data on sire 1 and his offspring it seems that this sire carried no undesirable factors which would cause his daughters, if they had received a double dose of such factors, to be deficient in vigor or malformed. It appears, however, that he did possess an inheritance for a considerable range in milk yield and in percentage of butterfat.

RECORDS OF THE DAUGHTERS OF SIRE 2

The production records of the daughters of sire 2 are shown in Table 16.

TABLE 16.—*Production records of inbred and outbred daughters of sire 2 and of their dams and granddams*

[All records calculated to maturity]

Foundation cows					50 per cent daughters of sire 1				75 per cent daughters of sire 1				50 per cent daughters of sire 2				75 per cent daughters of sire 2			
Breeding	Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat		Cow No.	Milk	Butterfat	
		Pounds	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*		*Pounds*	*Per cent*	*Pounds*
Group 1: [1]																				
Grade Guernsey	84	11,219	4.79	537									[2] A–39	16,818	3.61	607				
Grade Guernsey (75% inbred)	92	13,686	4.81	658									[2] A–27	18,853	3.99	752	A–43	20,928	3.58	750
Grade Holstein	A–6	14,232	3.96	564									[2] A–15	15,416	3.40	524	A–50	12,881	3.61	466
																	A–51	17,378	3.36	585
Do	A–7	16,461	4.35	716									[2] A–32	19,229	3.28	631				
Do	A–13	16,934	3.93	666									[2] A–40	21,245	3.88	824				
Average		14,506	4.33	628										18,312	3.65	668				
Group 2: [3]																				
Grade Jersey	7	10,367	4.09	424	64	15,313	3.84	588					[4] A–20	14,551	3.51	511	A–36	20,800	3.50	728
Do	7	10,367	4.09	424	64	15,313	3.84	588					[4] A–37	19,903	3.58	713				
Do	7	10,367	4.09	424	64	15,313	3.84	588					[4] A–42	19,466	3.45	672				
Do	21	15,647	4.56	714	91	19,926	3.91	779					[4] A–19	22,089	3.34	738	A–53	20,072	3.57	717
Average		11,687	4.25	496		16,466	3.86	636						19,000	3.47	658				
Group 3: [5]																				
Grade Jersey	20	6,350	4.23	269	63	11,213	3.24	363	94	19,930	3.17	632	A–28	15,405	3.57	550				
Do	23	9,308	4.17	388	82	18,131	3.68	667	A–2	19,682	3.49	687	A–21	17,615	3.18	560	A–45	18,307	2.80	512
Do	23	9,308	4.17	388	82	18,131	3.68	667	A–2	19,682	3.49	687	A–30	15,606	3.26	509				
Grade Holstein	29	17,416	4.18	728	51	19,072	3.78	721	A–3	17,106	3.61	618	A–26	25,434	3.36	855				
Grade Jersey	21	15,647	4.56	714	91	19,926	3.91	779	A–9	15,241	3.52	536	A–25	21,394	3.38	723	A–52	16,113	3.52	568
Do	21	15,647	4.56	714	91	19,926	3.91	779	A–9	15,241	3.52	536	A–38	13,906	3.23	449				
Average		12,279	4.34	533	4	17,733	3.73	662	4	17,814	3.46	616	6	18,227	3.33	608				

[1] All five of the 50 per cent daughters and two of the three 75 per cent daughters exceeded their dams in milk production. Three of the five 50 per cent daughters and one of the three 75 per cent daughters exceeded their dams in butterfat production. All five of the 50 per cent daughters and two of the three 75 per cent daughters were exceeded by their dams in percentage of butterfat.

[2] Out of foundation cows.

[3] Both of the 50 per cent daughters of sire 1, three of the four 50 per cent daughters of sire 2, and one of the two 75 per cent daughters of sire 2 exceeded their dams in milk production. Both of the 50 per cent daughters of sire 1, two of the four 50 per cent daughters of sire 2, and one of the two 75 per cent daughters of sire 2 exceeded their dams in butterfat production. All of the 50 per cent daughters of sires 1 and 2, and one of the two 75 per cent daughters of sire 2 were exceeded by their dams in percentage of butterfat.

[4] Out of 50 per cent daughters of sire 1.

[5] All four of the 50 per cent daughters of sire 1, two of the four 75 per cent daughters of sire 1, two of the six 50 per cent daughters of sire 2, and one of the two 75 per cent daughters of sire 2 exceeded their dams in milk production. Three of the four 50 per cent daughters of sire 1 and two of the six 50 per cent daughters of sire 2 exceeded their dams in butterfat production. Two of the four 75 per cent daughters of sire 1 and both of the 75 per cent daughters of sire 2 were exceeded by their dams in butterfat production. All of the four 50 per cent and all of the four 75 per cent daughters of sire 1 and five of the six 50 per cent and one of the two 75 per cent daughters of sire 2 were exceeded by their dams in percentage of butterfat.

In Table 16 the cows have been arranged in three groups. Group 1 shows the daughters by sire 2 out of foundation cows. Group 2 shows the daughters of sire 2 out of the 50 per cent outbred daughters of his own sire, sire 1. Group 3 shows the daughters of sire 2 out of his own sire's 75 per cent inbred daughters. Of the 5 foundation cows in group 1 mated with sire 2, 3 were grade Holsteins that probably carried the inheritance of some higher-testing breed; and the other 2 were grade Guernseys. One of these, cow 93, was a 75 per cent inbred daughter of the Guernsey sire used in the work on inbreeding grade Guernseys. The 4 foundation cows in group 2, granddams of the 4 daughters of sire 2 that were out of outbred daughters of sire 1, were all grade Jerseys. The 6 daughters of sire 2 that were out of inbred daughters of sire 1 were descended from the foundation cows in group 3, all of Jersey breeding except cow 29, a grade Holstein.

The five outbred daughters of sire 2 out of the grade Holstein and Guernsey foundation cows (group 1) all exceeded their dams in milk yield, although the latter had uniformly high records; but, like the outbred daughters of sire 1 from grade Jersey foundation cows, all were lower than their dams in percentage of butterfat. Three exceeded their dams in pounds of butterfat. Cow A–43, one of the three 75 per cent daughters of sire 2 in this group, has completed her record as a 2-year-old, with 20,928 pounds of milk and 750 pounds of butterfat, computed to a mature basis. As compared with her dam, she produced considerably more milk, a lower percentage of butterfat, and about the same total amount of butterfat. The granddam of this inbred heifer was a 75 per cent inbred daughter of the Guernsey sire discussed in this publication. These three generations of cattle show the typical decline in percentage of butterfat and the increase in milk-yield which takes place as the percentage of Holstein inheritance increases and the percentage of Guernsey inheritance decreases.

The two 75 per cent inbred daughters by sire 2 out of cow A–15 (group 1) which have completed their production records as 2-year-olds, are twin sisters. Apparently they are unlike twins in so far as color markings, level of milk yield, and percentage of butterfat are concerned. One produced 4,497 pounds more milk and 119 pounds more butterfat than the other, although the latter was the higher in percentage of butterfat by 0.25 per cent. One produced more milk and butterfat than the dam, and the other produced less than the dam. Here is another illustration of the fact that inbreeding will not result in a like level of production in the offspring if the sire to which they are inbred is himself heterozygous for level of production. Two of the three inbred daughters of sire 2 in this group are better than their dams in milk yield, two are below their dams in percentage of butterfat, and one is better, one poorer, and one approximately the same as the dam in yield of butterfat.

Of the 4 daughters of sire 2 (group 2) that are out of outbred daughters of sire 1, 3 are full sisters, A–20, A–37, and A–42. These 3 cows were all lower than their dam in percentage of butterfat, but 2 of them exceeded their dam in milk and 2 in butterfat yield. Cow A–20, the poorest producer of the 3, is the dam of cow A–36, a 75 per cent inbred daughter of sire 2. The latter showed a marked increase over her dam in both milk and butterfat yield. The other 75 per cent inbred daughter of sire 2 (A–53) in this group has three generations of high-producing dams in her immediate ancestry. In each of these previous generations the Holstein daughters had shown an

increase in milk yield and a decline in butterfat percentage from their Jersey foundation dam and granddam. In this 75 per cent inbred daughter of sire 2, representing the third successive cross of these Holstein sires, there is a slight increase in percentage of fat. Both of the 75 per cent daughters of sire 2 in this group are very high producers.

Group 3 in Table 16 is the most interesting since it shows the closest inbreeding. The six 50 per cent daughters of sire 2 in this group are out of four 75 per cent inbred daughters of sire 1. If average production of butterfat alone were considered in this group of four direct generations of cows, one might conclude that the inbreeding in the last two generations was resulting in a gradual decline in production. The average yield of butterfat for the foundation cows in this group was 533 pounds. The highest average, 663 pounds, was from the outbred daughters of sire 1, followed by an average of 616 pounds for the inbred daughters of sire 1, and 608 pounds for the 50 per cent (inbred) daughters of sire 2. These averages, however, include duplicate records for 2 foundation cows, 2 outbred daughters, and 2 inbred daughters of sire 1, because there were 2 pairs of full sisters in the fourth generation—the daughters of sire 2. If these duplicate records are excluded, the averages for production of milk, percentage of butterfat, and pounds of butterfat are: For the foundation cows, 12,180 pounds of milk, 4.31 per cent butterfat, and 525 pounds of butterfat; for the outbred daughters of sire 1, 17,086 pounds of milk, 3.70 per cent butterfat, and 632 pounds of butterfat, and for the inbred daughters of sire 1, 17,989 pounds of milk, 3.43 per cent butterfat, and 618 pounds of butterfat. The figures for the 50 per cent daughters of sire 2 are as given in the table, 18,227 pounds of milk, 3.33 per cent butterfat, and 608 pounds of butterfat. Excluding these duplicate records does not affect the relative ranking of the different generations in butterfat yields, though it does considerably reduce the difference between the outbred and the inbred daughters of sire 1 in butterfat yield. There is an increase in average yield of milk for each of the three generations of Holstein inheritance notwithstanding the increase in intensity of inbreeding. The decline in average butterfat yield is caused by the decline in percentage of butterfat. The decline in percentage of butterfat is caused by the increasing influence of the low-butterfat-percentage inheritance of these two Holstein sires and by the lessening influence of the high-butterfat-percentage inheritance of the foundation cows.

The 4 outbred daughters of sire 1 (group 3) were all better than their dams in milk yield by a wide margin, and all 4 were lower in percentage of butterfat. The milk yield of the 2 daughters of the 2 lowest-producing foundation cows was almost twice that of their dams. In the next generation only 2 of the 4 inbred daughters were better in milk yield that their outbred dams; the daughters of the 2 poorer cows gave more milk, but the daughters of the 2 better cows gave less milk than their dams. On the whole, it appears that the inbred daughters of sire 1 in this group did not quite hold their own. Two of the 4 were better in milk yield and pounds of butterfat, and all 4 were poorer in percentage of butterfat.

Of the 6 daughters by sire 2 which were out of these 4 inbred daughters of sire 1 (group 3), only 2 were better than their dams in milk and butterfat yield, but these 2 exceeded their dams by a sufficient margin to raise the average for the 6 daughters over that of the dams. There are 2 pairs of full sisters among these 6 daughters.

Both of the daughters of cow A–2 were lower than their dam in milk yield, percentage of butterfat, and pounds of butterfat. One of the 2 daughters of cow A–9 was considerably better, and the other considerably poorer, in milk and butterfat yield than her dam. On the whole, the records of these 6 daughters of sire 2, with milk yields ranging from 13,906 pounds to 25,434 pounds, are sufficiently high so that it does not seem that the relatively low production of 4 of them should be attributed to any weakened vigor of constitution resulting from inbreeding. Rather, it would appear that their comparatively low production is due to a heterozygous make-up for the factors determining varying levels of milk yield possessed by sires 1 and 2, and also to an inheritance for lower percentages of butterfat. Two inbred daughters of sire 2 that have completed their test are included in group 3. In some respects they are the most closely inbred animals shown in this study. Cow A–45, the inbred daughter of cow A–21, produced 18,307 pounds of milk and 512 pounds of butterfat. Her milk yield is greater than that of her dam, but the percentage of butterfat is considerably lower, resulting in a smaller amount of butterfat. The milk of this cow is lower in percentage of butterfat than that of any other daughter of sire 2. This cow (as her picture shows in Plate 4) at the age of 2 years was somewhat smaller and more refined in type than the other inbred daughters of sire 2, although she has since shown considerable development in form. Cow A–52, the other inbred daughter of sire 2 in this group, is considerably below her dam in both milk and butterfat production, but higher in percentage of butterfat.

Of the seven 75 per cent inbred daughters of sire 2 in these three groups, 4 are better than their dams in milk yield, 3 are better in percentage of butterfat and 2 are better and 1 is practically equal to her dam in butterfat yield. The average milk yield is a little greater than that of the dams, 18,068 pounds as compared to 17,905 pounds; but the average percentage of fat and the average fat yield are about the same.

There is no indication in the records or in the physical appearance of any of these inbred daughters of sire 2, except possibly in the case of cows A–28 and A–45, that producing capacity is being affected by loss of size or constitutional vigor as a result of inbreeding.

COLOR MARKINGS

Plate 4 shows that the first-generation cross with solid-color foundation cows did not bring out the characteristic Holstein spotting, nor did it breed the black off the legs below the knees and hocks. The first-generation cross with the broken-colored cow 23, however, did bring out the characteristic Holstein color markings, although some black was left below the knees. In most cases it has taken two or more crosses of Holstein breeding to bring out the spotting and to take off the black color from below the knees and hocks. In all cases the black of the Holstein has been dominant over red and all shades of fawn.

SUMMARY

In this inbreeding experiment grade dairy cows of mixed breeding and average production were mated to a good registered bull and the female offspring were mated back to their own sire for successive generations. The experiment in inbreeding Guernsey cattle was limited to the foundation Guernsey sire and two generations of

daughters. The experiment with Holsteins was carried on through several generations of inbred sons and grandsons of the first Holstein sire used, as well as daughters of these sires, and is being continued with the object of obtaining more definite and pronounced results.

With grade Guernseys it was found that: The birth weight of calves decreased as inbreeding became more intense. A few of the inbred calves were deformed at birth, the deformity apparently being due to a double dose of a recessive Mendelian factor which causes a definite type of deformity. The mature weight of the cows was reduced by inbreeding. The average milk production of both the 50 per cent and the 75 per cent daughters of the bull was about the same as that of the foundation cows, but on account of a progressive increase in the percentage of butterfat the 50 per cent daughters produced slightly more butterfat than their dams and the 75 per cent daughters produced somewhat more than did the 50 per cent daughters. The variations between the individuals in the production of milk and pounds of butterfat was less with the 50 per cent daughters than with the foundation cows and still less with the 75 per cent daughters.

With grade Holsteins it was found that: Inbreeding caused no decline in fertility, as judged by the services required for conception. The number of abortions and the normality of calves at birth did not appear to have been affected by inbreeding. The birth weights of the more intensely inbred calves were reduced to a marked extent. The mortality of calves after birth was greater with the inbred grades than with either the outbred grades or registered Holsteins, indicating a probable lack of vigor. Intensive inbreeding appears to depress the rate of growth of calves, although daughters of sire 1 showed no adverse effects in this respect. The mature inbred cows were considerably below the average mature weight of registered Holsteins raised under the same environmental conditions, but not proportionately so small as at birth. The production of milk increased and the percentage of butterfat decreased with the successive sire-daughter matings. The greatest improvement in the production of both milk and butterfat was in the first generation of outbred daughters; the increase in production of butterfat by succeeding generations of inbred daughters failed to equal that of the first generation. A concentration of the inheritance of sire 1 in his offspring reduced the coefficient of variability in yields of both milk and butterfat but not in percentage of butterfat. The birth weights of calves and the weights of mature cows were not depressed so markedly in the inbred Holsteins as they were in the inbred Guernseys.

In this experiment a bull that proved to possess an inheritance for a high level of milk production, mated with ordinary grade cows, brought about a big increase in production in the first-generation daughters. Subsequent improvement through inbreeding was slow. It is possible to obtain a good producing herd in one generation by the use of a sire that has proved his ability to transmit high production. Probably the hereditary make-up of the bull will influence production more than the system of breeding. Only a few sires have been used in this investigation and the number of cows available for comparison is small in many cases. While the data presented show some very definite trends and contribute information of value in the general study of the effects of inbreeding, it is not unlikely that results of close inbreeding with other sires would differ somewhat from those recounted here, depending upon the hereditary make-up of the sire used.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Dairy Industry	O. E. REED, *Chief.*
Division of Dairy Cattle Breeding, Feeding, and Management.	R. R. GRAVES, *Principal Specialist in Dairy Cattle Breeding, Chief.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

TECHNICAL BULLETIN No. 338 FEBRUARY, 1933

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

RELATION OF LEAF AREA AND POSITION TO QUALITY OF FRUIT AND TO BUD DIFFERENTIATION IN APPLES[1]

By M. H. HALLER, *Assistant Pomologist*, and J. R. MAGNESS, *Principal Pomologist, Division of Horticultural Crops and Diseases, Bureau of Plant Industry*

CONTENTS

	Page
Introduction	1
Material and methods	2
Relation of leaf area to growth and composition of apples	4
Increase in size of fruit	5
Chemical composition	10
Dessert quality	12
Firmness	13
Color development	13
Relation of distance and direction of fruit from leaves to size and composition of apples	15
Relation of leaf distance to growth of fruit	
Relation of direction of apples from leaves to growth of fruit	19
Relation of distance and direction of fruit from leaves to size and composition of apples—Continued.	
Relation between number of seeds per apple and size of fruit	20
Relation between leaf distance and chemical composition of fruit	20
Relation of leaf area per apple to bud differentiation	22
Review of previous work	22
Results of present investigations	25
Discussion	29
Summary	32
Literature cited	33

INTRODUCTION

The average mature apple consists of about 85 per cent of water and 15 per cent of dry matter, the latter consisting primarily of organic matter elaborated in the leaves. It is natural to suppose, therefore, that the growth and composition of the fruit would depend largely on the amount of water supplied to the fruit and on the elaborated foods available in the leaves. Obviously a liberal supply of moisture is essential for the proper development of the fruit. However, the rôle of elaborated foods supplied by the leaves is not so apparent. In this regard the relationship of leaf area to growth and composition of the fruit appears to be of importance, particularly with reference to the carbohydrate supplied to the fruit. The purpose of the investigation reported herein was to obtain definite information as to the relation of the carbohydrate supply to the growth and composition of the fruit. Another phase of this investigation, closely associated with carbohydrate supply, was the effect of fruiting on bud differentiation.

The supply of carbohydrates available to the fruit depends primarily on two factors—the amount of carbohydrates elaborated per fruit, and the transport of the carbohydrates to the fruit.

[1] Presented by the senior writer to the faculty of the graduate school of the University of Maryland in partial fulfillment of the requirements for the degree of doctor of philosophy.

146102—33——1

The amount of carbohydrates elaborated per fruit will depend first upon the leaf area per fruit. The leaf area per fruit may be influenced by certain orchard practices such as thinning, pruning, and fertilizing. Pruning usually increases the leaf area per fruit by reducing the number of fruiting spurs and thus stimulating the growth and leaf development in those that remain, but it may reduce the leaf area per fruit by increasing the set of fruit per spur. Nitrogen fertilizers also increase the leaf area by increasing vegetative vigor and thus the size of the leaves, but on the other hand they may reduce the leaf area per fruit by increasing the set of fruit. Thinning the fruit is the most effective method of increasing leaf area per fruit.

With a given leaf area per fruit the amount of carbohydrates formed will depend on the efficiency of the leaves, which in turn may be influenced by such factors as temperature, moisture, amount of chlorophyll, mineral nutrients, the amount of carbon dioxide in the surrounding atmosphere, and the duration and intensity of sunlight.

Factors that might influence the transport of carbohydrates to the fruit are (1) the diffusion gradient to the fruit and to other parts of the tree, (2) the distance and direction of the leaves from the fruit, and (3) the cross-sectional diameter of the conducting tissue at its narrowest point. The seed content of the fruit also seems to have some effect on the accumulation of elaborated foods in the fruit.

This bulletin deals with (1) the growth and composition of the fruit in relation to the carbohydrate supply as influenced by the leaf area per apple, (2) the transport of the carbohydrates to the fruit as influenced particularly by the distance and direction of the leaves from the fruit, and (3) the effect of fruiting on bud differentiation.

MATERIAL AND METHODS

The trees used in this investigation were located in the variety orchard at the Arlington Experiment Farm, Rosslyn, Va., near Washington, D. C. The experiments usually were started in June or the latter part of May, when the apples were about one-half to 1 inch in diameter.

Treatments were applied to both ringed and unringed branches. In ringing the branches a strip of bark about one-quarter inch wide was removed, the cambium was scraped, and melted paraffin was applied to the wound. Scraping the cambium prevented regeneration of phloem across the ring; this treatment would also prevent the development of new xylem tissue at the ring. Apparently greater injury to the branches resulted when the ringing was done very early in the season than when it was done later, probably because of the reduction in the amount of new xylem tissue, which would probably be more active in the translocation of water to the branch. Similarly, the smaller the branch the greater was the injury. For this reason, after the first year fairly large branches, at least 2.5 cm in circumference, were used in order to reduce this injury as much as possible. Larger branches, at least 6 cm in circumference, were used for the unringed branches.

To study the effect of leaf area on the fruit and on bud differentiation, leaves or fruit were removed from both ringed and unringed branches until the desired number of leaves per fruit was obtained.

To study the effect of the leaf position on the fruit, unringed branches from which all of the leaves were removed were used. On such branches the fruit was at varying distances from the leaves on the main limbs to which the branches were attached. These leaves would be the nearest source of elaborated food. The distances from the main limbs to the fruits were measured along the shortest possible paths through the branches. Ringed branches were also used, on which 1 fruit and 20 leaves were left above the ring on each branch, the leaves being left at varying distances from the fruit. In some cases the leaves were left as close as possible to the fruit, as in Figure 1, A; in others they were left 50 to 100 cm or more from the fruit. In some cases the leaves were above the fruit, as in Figure 1, B, while in others they were below the fruit or on separate branches, as in Figure 1, C. In another experiment ringed branches were used on which 20 leaves and 2 fruits were left above the ring, one of the fruits being distant from the leaves, whereas the other was close, as shown in Figure 1, D.

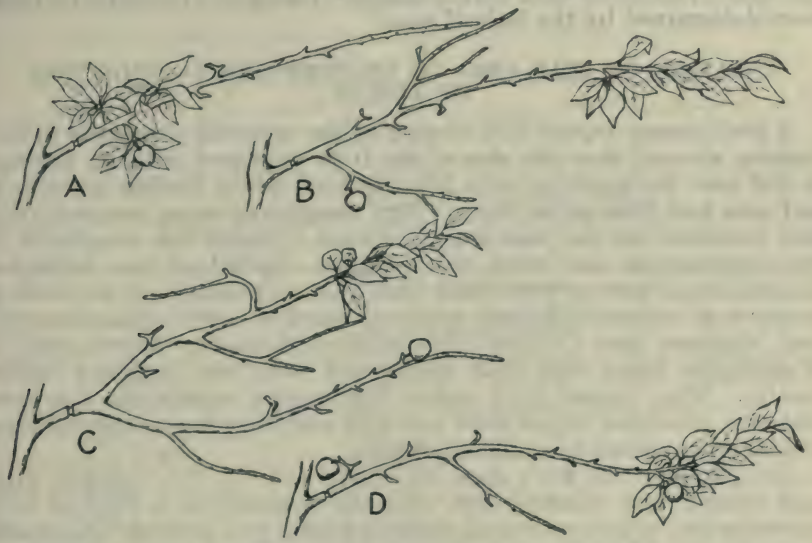


FIGURE 1.—Treatment of ringed branches: A, Leaves adjacent to apple; B, leaves distant from and above apple; C, leaves distant on separate branch from apple; D, leaves distant from one apple and adjacent to another

Small or deformed leaves were stripped off, leaving only the medium-sized and large ones. The area of at least 100 leaves similar to those on the test branches was measured by means of a planimeter, and the leaf area per apple was approximated from these measurements. In most cases all treatments for each variety were applied to a single tree or to two adjacent trees.

The circumference of the fruit at the widest transverse diameter was determined at the beginning of the experiments and at intervals thereafter until harvest. The volume of the fruit, assumed to be a sphere, was computed from the circumference measurements, and the increase in volume was obtained by subtracting the volume of each apple at the beginning of the experiment from the volume of the same apple when mature.

The fruit was harvested in the fall and grouped according to the number of leaves with which the apples were grown or according to the distance they were from the leaves. After it had been stored for a period in order to allow the starch to be changed to sugar, samples were taken, and sugar and acid determinations were made according to the methods described in a previous publication (*30*).[2] Dry-weight determinations were made in 1925 and 1926 by drying 25-g[3] samples of ground tissue to constant weight at 85° to 90° C. In 1927 direct determinations were made by distilling with toluol according to the method described by Bidwell and Sterling (*10*).

In the spring following the year in which the thinning treatments were made, blossom and leaf buds were counted on the spurs of the branches that were used for the leaf-area studies. Spurs that fruited during the year of treatment were tagged in 1926 and 1927 but not in 1925. Spurs that had blossomed but from which the fruit had dropped or had been removed were determined by the fruit scars on the spurs, and those that were leaf spurs during the year of treatment were determined by the lack of scars.

RELATION OF LEAF AREA TO GROWTH AND COMPOSITION OF APPLES

A preliminary report (*21*) of part of the material presented in this bulletin showed that the size of the fruit increased with an increase in leaf area per apple up to a point beyond which further increase in leaf area had little or no effect. Dry weight and sugar concentration also increased as the leaf area increased. Under the conditions of the experiments and with the varieties studied at the Arlington Experiment Farm, it was found that about 30 leaves are required to produce a commercial-sized apple of good quality. Magness (*28*) and Magness and Overley (*31*) conducted similar experiments in Washington State with both apples and pears and obtained similar results. They found that under Washington conditions the same leaf area produced larger fruit but with a slightly lower sugar concentration than under Virginia conditions.

According to the work done by Curtis (*14*, *15*, *16*), Gardner (*19*), and Mason and Maskell (*32*, *33*), the removal of a ring of bark prevents the translocation of carbohydrates and possibly of mineral nutrients in either direction past the ring. Thus, fruit grown above the ring would depend entirely on the leaves above the ring or on food stored above the ring for organic nutrients. Likewise, the food elaborated in leaves above the ring would be confined above the ring, and any excess material would not move out of the branch as it would in unringed branches. However, fruits on unringed branches are not necessarily dependent on food elaborated in adjacent leaves, but may draw upon food elaborated in adjacent branches, and food elaborated in leaves on the unringed branch may be translocated to other parts of the tree. For these reasons ringing is necessary in order to obtain a critical reading of the leaf area that is required to build the nutrient material utilized in the development of a fruit. Results obtained from experiments on ringed branches, however, are not directly comparable with those obtained from experiments on unringed branches.

---

[2] Italic numbers in parentheses refer to Literature Cited, p. 33.

[3] g is the abbreviation for gram or grams, and cm^3 and cm^3 are the abbreviations for square and cubic centimeters recently adopted by the Style Manual for U. S. Government printing.

INCREASE IN SIZE OF FRUIT

Table 1 shows the coefficients of correlation between the increase in volume of the fruit and the number of leaves per apple for fruit grown on ringed branches. The correlations are positive and significant in all cases and are even higher when the fruit grown with the greater leaf areas is not considered. For example, in the Ben Davis apples for 1925 a correlation of $+0.743 \pm 0.028$ was obtained when all the fruit was considered, whereas a correlation of $+0.933 \pm 0.01$ was obtained when only the fruit grown with 5 to 30 leaves each was considered, indicating less increase in size of the fruit when grown with the larger leaf areas. This is brought out more clearly in Figure 2, in which the increase in volume per 10-day interval is plotted against the leaf area per apple. Figure 2 shows a rapid increase in volume with an increase in leaf area up to about 300 to 500 cm² per fruit, depending on the variety. Above this range the fruit continues to increase in volume with an increase in leaf area, but the increase is relatively slight.

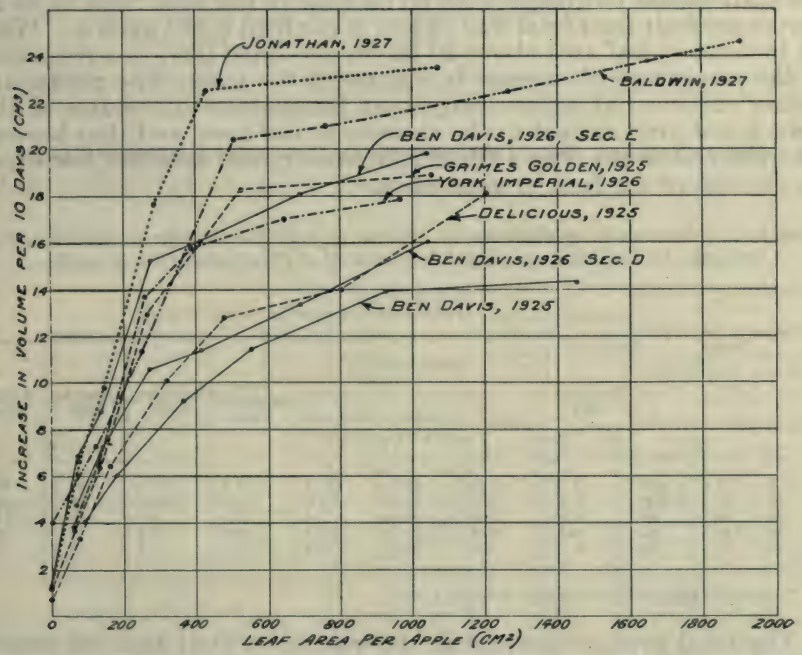


FIGURE 2.—Average increase in volume of apples at 10-day intervals in relation to the leaf area per apple on ringed branches. ("Sec. D" and "Sec. E" refer to trees in different sections of the orchard to which treatments were applied at different times)

TABLE 1.—*Coefficients of correlation between the increase in volume of different varieties of apples and the number of leaves per apple on ringed branches*

Variety	Year	Number of leaves	Correlation	Variety	Year	Number of leaves	Correlation
Rome Beauty	1924	1 to 20	+0.975±0.002	Ben Davis	1926	5 to 75	+0.696±0.033
Ben Davis	1924	4 to 20	+ .594± .038	Do	1926	0 to 75	+ .760± .031
Delicious	1924	4 to 20	+ .423± .044	York Imperial	1926	5 to 75	+ .673± .031
Ben Davis	1925	5 to 75	+ .743± .028	Baldwin	1927	0 to 75	+ .704± .029
Delicious	1925	0 to 75	+ .805± .017	Jonathan	1927	0 to 75	+ .800± .029
Grimes Golden	1925	0 to 80	+ .829± .009				

In most cases increase in volume of fruit is not directly proportional to the increase in leaf area. Thus, doubling the leaf area from 5 leaves to 10 or from 10 leaves to 20 does not double the size of the fruit. This indicates that the practice of thinning, although increasing the size of fruit, would reduce the total crop per tree. This is shown more clearly in Table 2, which gives the percentage increase in the volume of the fruit in relation to the percentage of increase in leaf area. With 100 per cent increase in leaf area, that is, from 5 leaves to 10 leaves per fruit, there was an average increase of only 56.4 per cent in the volume of the fruit for all varieties. Increasing the leaf area from 10 to 20 leaves per fruit increased the average volume of all varieties 71.5 per cent. In the York Imperial and Grimes Golden varieties the percentage of increase in the volume of the fruit was greater than the percentage of increase in the leaf area, being 110.1 per cent for York Imperial and 103.5 per cent for Grimes Golden. The latter is not shown in Table 2. These two cases are probably due to experimental error. Why the percentage of increase in volume of the fruit should be greater with an increase in leaf area from 10 to 20 leaves per fruit than from 5 to 10 leaves per fruit is not known. With an increase in leaf area above 20 leaves per apple there is a reduction in the percentage of increase in volume of the fruit. The results are rather variable but show clearly that the increase in volume of the fruit is not proportional to the increase in leaf area, and that beyond 20 to 30 leaves per fruit a further increase in leaf area has less effect on the size of the fruit in most cases.

TABLE 2.—*Percentage of increase in volume of fruit in relation to percentage of increase in leaf area on ringed branches of different varieties of apple*

Increase in leaves per fruit			Percentage of increase in volume of fruit							
				Ben Davis						
From—	To—	Per cent	Delicious, 1925	1925	1926, first lot [1]	1926, second lot [1]	York Imperial, 1926	Baldwin, 1927	Jonathan, 1927	Average
5	10	100	93.3	47.9	49.1	27.2	72.5	57.0	47.6	56.4
10	20	100	56.9	53.2	47.5	74.0	110.1	78.2	80.4	71.5
20	30	50	26.8	25.6	8.0	5.4	15.0	2.9	27.5	15.9
30	50	67	9.3	20.2	17.2	12.7	8.0	7.1	1.7	10.9
50	75	50	29.2	2.8	19.4	9.4	5.0	9.8	2.6	11.2

[1] Treatments applied to two trees at different times.

The total average increase in the volume of fruit both on ringed branches and on those not ringed is shown in Table 3. The increase in volume, by 10-day intervals, of fruit on branches that were not ringed is shown in Figure 3. It will be observed that while the tendency for fruit on unringed branches is to increase in size with an increase in leaf area, the increase in size was not nearly so decided nor consistent as on ringed branches, and in a few cases there was a decrease in size with an increase in leaf area. Fruit on unringed branches with a very small leaf area was usually larger than fruit with the same leaf area on ringed branches, whereas fruit on unringed branches with a large leaf area was usually smaller than the corresponding fruit on ringed branches. In all cases fruit grown on unringed

branches from which all the leaves had been stripped was as large as, or larger than, fruit on ringed branches with 10 leaves per fruit. With the exception of the Delicious variety in 1925, fruit grown on

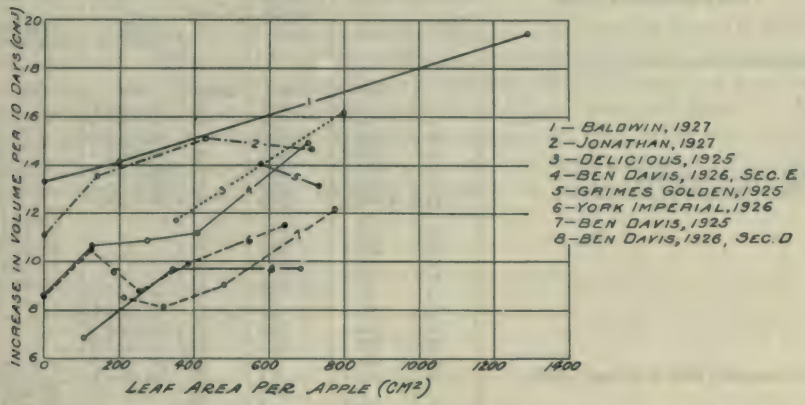

INCREASE IN VOLUME PER 10 DAYS (CM³)
LEAF AREA PER APPLE (CM²)
1 — BALDWIN, 1927
2 — JONATHAN, 1927
3 — DELICIOUS, 1925
4 — BEN DAVIS, 1926, SEC. E
5 — GRIMES GOLDEN, 1925
6 — YORK IMPERIAL, 1926
7 — BEN DAVIS, 1925
8 — BEN DAVIS, 1926, SEC. D

FIGURE 3.—Average increase in volume of apples at 10-day intervals in relation to the leaf area per apple on unringed branches. ("Sec. D" and "Sec. E" refer to trees in different sections of the orchard to which the treatments were applied at different times)

unringed branches with 50 leaves per fruit was as small as, or smaller than, fruit grown on ringed branches with 20 leaves per fruit.

TABLE 3.—*Relation of leaf area per apple to increase in volume of fruit*

Variety and date of ringing	Leaves per fruit		Volume of fruit at beginning of test	Period of growth	Increase in volume of fruit on—	
	Number	Area			Ringed branches	Unringed branches
		Cm²	*Cm³*	*Days*	*Cm³*	*Cm³*
Delicious, May 8 to June 4, 1925	0	0	13.8	85	5.6±0.5	
	5	80.3	12.7	85	28.3±1.4	
	10	160.6	14.3	85	54.7±1.7	
	20	321.2	13.9	85	85.8±2.4	
	30	481.8	16.1	85	108.8±2.5	
	50	803.0	14.9	85	118.9±4.0	
	75	1,204.5	17.9	85	153.6±9.4	
	22	353.3	13.7	85		99.4±3.9
	50	803.0	17.5	85		138.3±1.6
Grimes Golden, June 17–18, 1925	0	0	24.3	68	7.2± .3	
	5	65.8	23.1	68	25.3± .7	
	10	131.6	22.4	68	43.1±1.6	
	20	263.2	21.6	68	87.7±1.8	
	40	526.4	22.3	68	124.2±2.8	
	80	1,052.8	22.3	68	128.4±4.3	
	44	579.0	23.6	68		97.3±1.6
	56	736.9	21.4	68		88.8±1.8
Ben Davis: June 3–5, 1925	5	92.6	11.8	107	43.4±3.1	
	10	185.2	11.5	107	64.2±2.7	
	20	370.4	12.2	107	98.4±2.6	
	30	555.6	11.5	107	123.6±2.4	
	50	926.0	13.2	107	148.6±3.6	
	75	1,389.0	12.7	107	152.8±4.5	
	12	222.2	12.7	107		94.0±3.4
	17	314.8	11.2	107		87.2±2.6
	26	481.5	12.7	107		100.0±2.3
	42	777.8	14.0	107		129.8±2.3
Ben Davis: May 15–19, 1926	5	69.3	1.3	112	54.0±2.2	
	10	138.7	1.0	112	80.5±2.0	
	20	277.4	1.0	112	118.7±4.3	
	30	416.1	.9	112	128.2±4.7	
	50	693.5	.8	112	150.3±6.8	
	75	1,040.2	1.1	112	179.4±5.4	
	6	83.2	1.1	112		76.8±1.5
	25	346.7	1.2	112		109.4±3.4
	50	693.5	1.0	112		109.2±3.3

TABLE 3.—*Relation of leaf area per apple to increase in volume of fruit*—Con.

Variety and date of ringing	Leaves per fruit		Volume of fruit at beginning of test	Period of growth	Increase in volume of fruit on—	
	Number	Area			Ringed branches	Unringed branches
		Cm²	*Cm³*	*Days*	*Cm³*	*Cm³*
Ben Davis—Continued. June 24–25, 1926	0	0	21.7	76	9.1±0.4	
	5	69.3	22.6	76	52.3±2.3	
	10	138.7	23.9	76	66.5±3.7	
	20	277.4	23.2	76	115.7±3.0	
	30	416.1	23.5	76	122.0±4.9	
	50	693.5	24.9	76	137.5±5.1	
	75	1,040.2	25.0	76	150.4±6.0	
	0	0	27.8	76		65.5±1.8
	10	138.7	27.5	76		81.5±2.3
	20	277.4	23.9	76		82.5±2.0
	30	416.1	24.5	76		85.0±1.3
	51	707.4	31.4	76		113.0±2.8
York Imperial, May 27 to June 2, 1926	5	64.8	7.7	73	27.6±1.0	
	10	129.7	8.5	73	47.6±1.9	
	20	259.4	10.2	73	100.0±2.4	
	30	389.1	10.1	73	115.0±4.6	
	50	648.5	9.6	73	124.2±3.8	
	75	972.7	9.1	73	130.4±4.6	
	0	0	10.6	73		62.3±2.3
	10	129.7	9.3	73		78.2±1.9
	20	259.4	9.6	73		63.9±1.1
	30	389.1	9.6	73		72.3±1.4
	50	648.5	10.3	73		84.3±1.8
Baldwin, June 3–10, 1927	0	0	25.2	91	36.4±3.6	
	5	127.1	27.6	91	66.3±3.7	
	10	254.2	27.9	91	104.1±3.5	
	20	508.4	31.9	91	185.5±3.9	
	30	762.6	27.3	91	190.8±5.2	
	50	1,271.0	24.7	91	204.4±9.0	
	75	1,906.5	23.3	91	224.4±8.5	
	0	0	28.5	91		121.2±1.9
	8	203.4	22.5	91		128.5±2.5
	51	1,296.4	39.7	91		176.5±3.4
Jonathan, June 20–24, 1927	0	0	34.7	64	8.6±0.9	
	5	71.9	35.3	64	42.4±1.5	
	10	143.9	34.6	64	62.6±2.0	
	20	287.8	40.8	64	112.9±3.1	
	30	431.7	43.0	64	143.9±3.9	
	50	719.5	42.4	64	146.4±3.5	
	75	1,079.2	42.0	64	150.2±3.6	
	0	0	33.4	64		69.5±1.6
	0	0	36.5	64		71.9±1.5
	10	143.9	32.1	64		87.7±2.7
	30	431.7	35.6	64		97.6±2.3
	50	719.5	38.1	64		94.5±2.8

In general, trees bearing a medium to heavy crop were used for these investigations, so that the average leaf area for the tree as a whole was probably about 20 leaves per apple. The fruit on unringed branches seemed to respond, therefore, according to the number of leaves per apple on the tree as a whole rather than according to the number of leaves per apple on the experimental branches.

The discrepancies between the results obtained on ringed and on unringed branches can be explained by the data presented in the portion of this bulletin dealing with the relation of the distance and direction of the fruit from the leaves to the size and composition of apples (pp. 15 to 22), in which it is shown that there may be considerable translocation from a branch with a light crop of fruit to one with a heavy crop. There is also a relatively large use of synthesized materials in building trunk and root tissue, much of which probably comes from leaves on lightly loaded branches. Thus, the fruit grown on unringed branches with few or no leaves per fruit undoubtedly drew upon elaborated foods in adjacent branches,

while much of the elaborated food in the branches with large leaf area per fruit was translocated to adjacent branches that were more heavily loaded with fruit or to other parts of the tree. This relation is also brought out in Plate 1, in which the apples from unringed branches are shown directly below those from ringed branches grown with the same number of leaves.

Figure 4 shows the increase in the size of the apples per 10 days per 645 cm² (100 square inches) of leaf area when grown on ringed branches. An apparent decrease is shown in the efficiency of a given leaf area correlated with an increase in the leaf area per fruit, as 10 apples grown with 64.5 cm² (10 square inches) of leaf area per apple would have two to three times as great a volume as one apple grown with 645 cm² (100 square inches) of leaf area per apple.

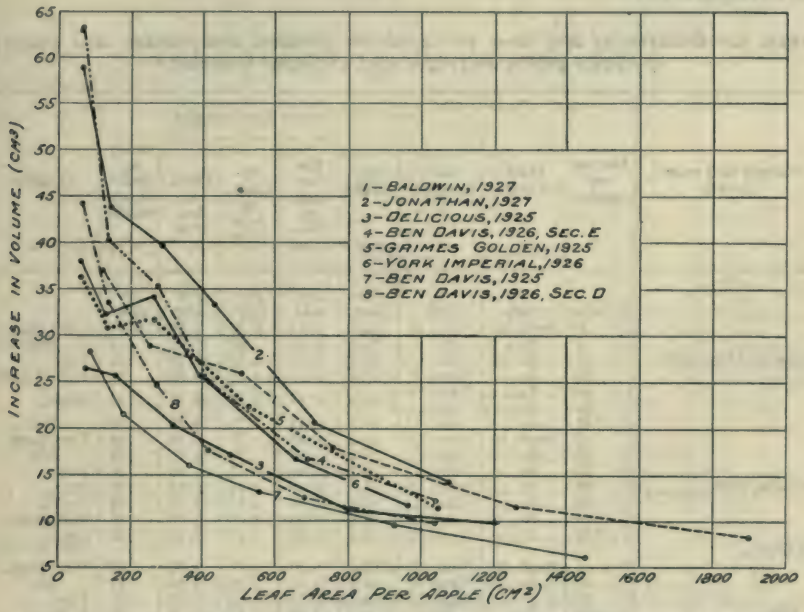


FIGURE 4.—Increase in volume of apples per 10 days per 645 cm² (100 square inches) of leaf area in relation to the leaf area per apple on ringed branches

The size of the fruit, however, is not a true index to the efficiency of the leaves, as a greater proportion of the elaborated food probably is used for other purposes, such as the growth of wood and buds, and storage in the wood and fruit on branches with a large leaf area per fruit. In this connection much greater callus formation at the ring has been observed on branches with a large number of leaves per fruit, indicating storage or utilization of elaborated food at this point. Even so, there is probably a reduction in the efficiency of the leaves, due to an accumulation of the products of photosynthesis in such branches. Leaves on ringed branches with 50 and 75 leaves per apple were observed to be lighter green than leaves on other parts of the tree, and frequently some of these leaves became yellow and dropped prematurely.

CHEMICAL COMPOSITION

Table 4 shows the data on the chemical analyses of the fruit from both ringed and unringed branches. The fruit was kept in storage at 40° F. for a period before it was sampled, so that the starch would be converted to sugar. The sugar content would then be at its maximum and more nearly represent the total carbohydrates in the fruit. However, it was not always possible to do the sampling at the proper time, so in some cases the fruit was in storage longer than was desirable. Slight changes in the proportion of the various constituents and probably slight reduction in total sugars and acid, due to respiration, would result from long storage periods. These variations, however, would not be large; and since all the sampling was done at practically the same time for each variety, the results are comparable.

TABLE 4.—*Relation of leaf area per apple to chemical composition and quality of apples grown on ringed and unringed branches* [1]

Variety and year grown	Leaves per apple	Date harvested	Date sampled	Dry weight	Sugars (fresh weight)			Acid, as malic (fresh weight)	Quality
					Reducing, as dextrose	Sucrose, as dextrose	Total, as dextrose		
	Number	1925	1925	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
Grimes Golden, 1925	0	Sept. 15	Nov. 10	12.7	7.43	0.37	7.80	0.31	Very poor.
	5	...do...	...do...	15.3	10.05	1.60	11.65	.32	Do.
	10	...do...	...do...	16.1	9.88	2.22	12.10	.29	Poor.
	20	...do...	Nov. 9	17.3	9.53	4.37	13.90	.34	Fair to good.
	40	...do...	Nov. 5	18.8	8.98	5.37	14.35	.35	Good.
	80	...do...	...do...						
	[2] 44	...do...	...do...	16.8	9.43	4.27	13.70	.30	Do.
Delicious, 1925	5	Sept. 19	Nov. 12	11.2	7.83	.27	8.10	.24	Very poor.
	10	...do...	...do...	11.9	9.28	.77	10.05	.18	Do.
	20	...do...	...do...	13.3	10.85	.75	11.60	.20	Poor.
	30	...do...	Nov. 11	15.7	10.43	1.92	12.35	.20	Fair.
	50	...do...	...do...	18.1	10.98	3.47	14.45	.23	Good.
	75	...do...	...do...	19.4	12.23	3.72	15.95	.25	Very good.
	[2] 50	...do...	Nov. 13	15.2	10.38	2.07	12.45	.23	Good.
Ben Davis:									
1925	5	Sept. 26	Nov. 16	12.6	8.28	1.12	9.40	.32	Very poor.
	10	...do...	Nov. 14	12.7	8.25	1.60	9.85	.34	Do.
	20	...do...	Nov. 13	14.1	9.18	1.82	11.00	.31	Poor.
	30	...do...	...do...	16.9	9.28	3.12	12.40	.36	Fair.
	50	...do...	...do...	18.1	9.13	4.17	13.30	.44	Good.
	75	...do...	...do...	19.4	9.63	5.52	15.15	.46	Do.
	[2] 42	...do...	Nov. 17	15.4	8.95	2.80	11.75	.31	Fair.
		1926	1927						
1926	0	Sept. 11	Mar. 14	9.2	5.74	.26	6.00	.36	Very poor.
	5	...do...	Mar. 12	9.0				.30	Poor.
	10	...do...	Mar. 11	10.2	7.78	.78	8.56		Do.
	20	...do...	...do...	10.6				.33	Poor to fair.
	30	...do...	...do...	12.9	7.82	2.14	9.96	.34	Fair.
	50	...do...	Mar. 9	12.8					Fair to good.
	75	...do...	...do...	13.6	7.70	3.18	10.88	.37	Do.
	[2] 0	Sept. 13	...do...	9.8	7.39	.73	8.12	.30	
	[2] 6	Sept. 11	Mar. 15	11.1	7.66	.86	8.52	.32	Fair.
	[2] 10	Sept. 13	Mar. 17	9.7	7.26	.78	8.04	.39	Do.
	[2] 20	...do...	Mar. 16	10.8	7.46	1.06	8.52	.29	Do.
	[2] 25	Sept. 11	Mar. 14	11.0	7.68	.72	8.40	.30	Do.
	[2] 30	Sept. 13	Mar. 16	10.0	7.44	.72	8.16	.29	Do.
	[2] 50	Sept. 11	Mar. 14	11.6	7.86	1.34	9.20		Do.
	[2] 51	Sept. 13	Mar. 21	10.7	7.72	1.20	8.92	.34	Do.

[1] Unless otherwise indicated, data are for ringed branches.
[2] Grown on unringed branch.

TABLE 4.—*Relation of leaf area per apple to chemical composition and quality of apples grown on ringed and unringed branches*—Continued

Variety and year grown	Leaves per apple	Date harvested	Date sampled	Dry weight	Sugars (fresh weight)			Acid, as malic (fresh weight)	Quality
					Reducing, as dextrose	Sucrose, as dextrose	Total, as dextrose		
	Number			*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
		1926	1926						
	5	Sept. 23	Dec. 22	9.6	7.60	.52	8.12	.47	Very poor.
	10	...do.....	...do.....	10.7	7.94	1.34	9.28	.48	Poor.
	20	...do.....	Dec. 21	11.7	8.40	2.20	10.60	.46	Fair to good.
	30	...do.....	Dec. 20	13.8	8.66	4.06	12.72	.51	Good.
	50	...do.....	...do.....	14.8	7.94	4.78	12.72	.49	Do.
	75	...do.....	...do.....	16.6	8.52	5.88	14.40	.55	Very good.
			1927						
York Imperial, 1926	[1] 0	...do.....	Jan. 13	13.1	8.94	1.09	10.03	.39	Good to fair.
	[1] 10	...do.....	Jan. 7	14.1	8.48	2.68	11.16	.46	Do.
			1926						
	[1] 20	...do.....	Dec. 23	12.2	8.66	2.22	10.88	.40	Do.
			1927						
	[1] 30	...do.....	Jan. 11	14.5	9.30	2.58	11.88	.35	Do.
	[1] 50	...do.....	Jan. 5	14.4	9.10	2.06	11.16	.40	Good.
		1927	1928						
	0	Aug. 30	Jan. 20	13.7	7.1	.4	7.5	.58	Very poor.
	5	...do.....	Jan. 19	14.8	9.2	.4	9.6	.53	Poor.
	10	...do.....	...do.....	16.3	9.6	.6	10.2	.56	Fair.
	20	...do.....	Jan. 18	17.7	9.8	1.8	11.6	.69	Fair to good.
	30	...do.....	...do.....	18.6	9.8	3.6	13.4	.81	Good.
Jonathan, 1927	50	...do.....	Jan. 17	21.7	10.5	4.5	15.0	.90	Very good.
	75	...do.....	Jan. 16	20.6	9.7	4.1	13.8	.97	Do.
	[1] 0	...do.....	Jan. 24	16.2	9.7	1.0	10.7	.54	Good to fair.
	[1] 10	...do.....	Jan. 23	17.6	9.8	1.6	11.4	.65	Good.
	[1] 30	...do.....	Jan. 21	18.0	10.0	1.6	11.6	.67	Do.
	[1] 50	...do.....	...do.....	19.0	10.2	1.6	11.8	.68	Do.
			1927						
	0	Sept. 8	Mar. 14	12.2	6.8	.4	7.2	.42	Very poor.
	5	...do.....	...do.....	12.4	7.7	.8	8.5	.50	Do.
	10	...do.....	...do.....	14.5	8.2	1.9	10.1	.51	Poor.
	20	...do.....	Mar. 13	15.6	7.8	3.6	11.4	.54	Good.
	30	...do.....	Mar. 12	18.1	8.8	4.0	12.8	.57	Good to very good.
Baldwin, 1927	50	...do.....	Mar. 10	18.6	8.6	4.6	13.2	.59	Do.
	75	...do.....	...do.....	20.3	9.1	5.9	15.0	.67	Do.
	[1] 0	...do.....	Mar. 21	14.7	7.8	2.2	10.0	.55	Fair to good.
	[1] 8	...do.....	Mar. 17	15.6	7.8	3.2	11.0	.57	Good.
	[1] 51	...do.....	Mar. 19	15.2	7.9	2.7	10.6	.71	Do.

[1] Grown on unringed branch.

With an increase in leaf area per apple there was an increase in the percentage of dry weight and an increase in total sugars for apples on ringed branches. (Table 4 and fig. 5.) The increase in total sugars is due principally to an increase in sucrose, since the free-reducing sugars remained practically constant except for slight increases in apples grown with from 0 to 5 leaves per fruit and in some cases with from 5 to 10 leaves per fruit. Above 10 leaves there was no significant change in the reducing sugars. The percentage of sucrose was usually 5 to 10 times as much in the apples grown with 50 to 75 leaves as in apples grown with only 5 leaves.

The variations in the results of the acid determinations were not so great or clear-cut as those of the sugar determinations. In general there seemed to be an increase in acidity with large leaf areas. With

very small leaf areas, however, there was in some cases an increase in acidity with a decrease in leaf area.

On unringed branches there was no consistent variation in any of the constituents determined, associated with the leaf area per apple on the branch. In general the composition of fruit on unringed branches, regardless of the number of leaves per apple, was similar to that on ringed branches with 20 to 30 leaves per apple.

DESSERT QUALITY

The dessert quality of the fruit grown on ringed branches varied greatly, depending on the leaf area. All fruit grown on ringed branches without leaves was bitter and sour, with a disagreeable flavor and a coarse, woody texture. Such fruit was small and green and apparently had changed little in either appearance or eating

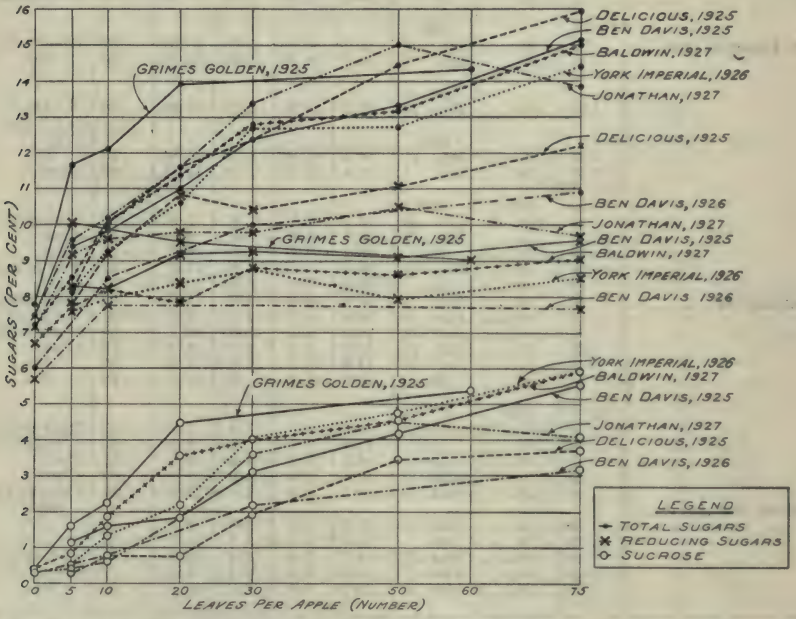
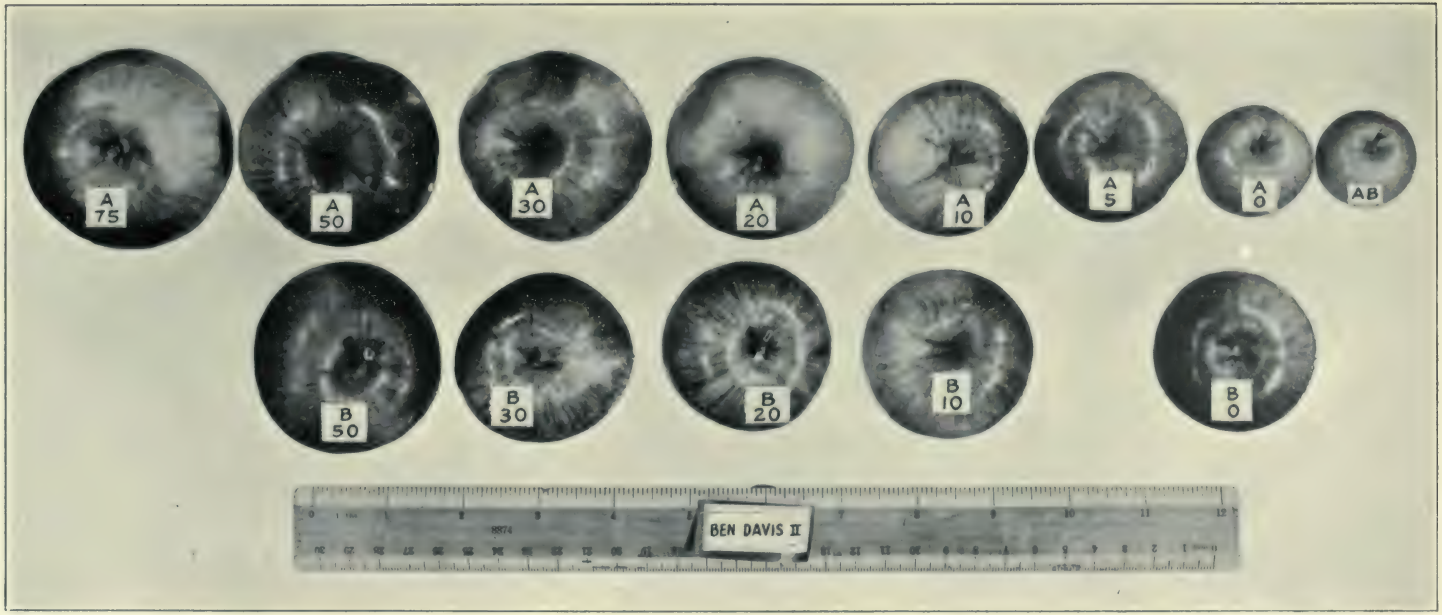


FIGURE 5.—Leaf area per apple in relation to percentage of sugar in apples on ringed branches

quality from its condition at the time the treatments were applied. (Pl. 1.) Fruit grown with only five leaves per apple was very little better than that grown without leaves; however, the texture of the flesh was usually less woody and the flavor somewhat less disagreeable. When the fruit was grown with 10 leaves per apple the quality was still poor, the flavor being rather bitter and disagreeable, although the texture was no longer woody. When grown with 20 leaves per apple, the fruit usually showed considerable improvement in quality, although in most cases it still lacked the sweetness and good flavor characteristic of the variety. This was particularly true of Delicious, which was still rather disagreeable in flavor, whereas Jonathan was fairly good. Baldwin also showed good quality with 20 leaves per fruit, but the leaves were so large that 20 of them gave a leaf area as large as that of 30 leaves of the other varieties. With 30 leaves per



Ben Davis apples grown in 1926 with various numbers of leaves per fruit as indicated by the number on the apple. Those marked "A" grown on ringed branches; those marked "B" grown on unringed branches. The apple marked "AB" represents the size of the fruit at the beginning of the experiment

fruit on ringed branches, the apples were usually of good average quality for the variety, and with 50 and 75 leaves per fruit the apples were of very good quality, being sweet and highly flavored and usually having a firm, crisp texture.

On unringed branches the number of leaves per fruit had no perceptible effect on the quality of the fruit.

FIRMNESS

The differences in the texture of the fruit are shown in Table 5, which gives the firmness of the fruit when sampled as measured by the pressure tester. In the case of Ben Davis there was a gradual decrease in firmness with an increase in leaf area. In the other three varieties (York Imperial, Baldwin, and Jonathan), however, the firmness decreased to about 20 leaves per fruit and then increased with a further increase in leaf area per fruit. The texture of fruit grown with a small leaf area differs greatly from that grown with a large leaf area even though the firmness as measured by the pressure tester may be about the same. In the case of fruit grown with a small number of leaves the flesh is woody and tough as in very green fruit, whereas the flesh of fruit grown with a large number of leaves was firm but crisp. The firmness of fruit grown with a very large leaf area would seem to indicate better storage quality for such fruit as compared with that grown with a smaller leaf area.

TABLE 5.—*Firmness of apples grown on ringed branches in relation to number of leaves per fruit*

Number of leaves per fruit	Pressure test (in pounds) at date of sampling				Number of leaves per fruit	Pressure test (in pounds) at date of sampling			
	York Imperial (1926)	Ben Davis (1926)	Baldwin (1927)	Jonathan (1927)		York Imperial (1926)	Ben Davis (1926)	Baldwin (1927)	Jonathan (1927)
0			12.5	12.1	30	[1] 15.3	13.6	11.6	7.7
5	22.8	19.1	10.3	8.0	50		13.1	12.5	8.5
10	19.8	15.7	10.1	7.7	75	18.2	12.6	14.3	9.0
20	14.0	14.1	10.2	7.1					

[1] Fruit with 30–50 leaves became mixed and 15.3 represents pressure test on mixture of two lots.

COLOR DEVELOPMENT

The importance of an accumulation of carbohydrates in apples in the development of red color has been pointed out in a previous report (*29*), in which an increase in solid-red color with an increase in leaf area has been shown for Delicious. Fletcher (*18*) found that 20 and 40 leaves for Rome Beauty and York Imperial, respectively, were necessary on ringed branches to produce normal color development. He also found increased color and sugar in apples when sugar in the form of "cerelose" was added to the soil. The development of red color in relation to leaf area is shown in Table 6 for apples grown on ringed branches. In general the data show an increase in red color with an increase in leaf area. There was considerable variation, however, and only in the case of Jonathan was there a consistent increase for all leaf areas. In most cases there is a decrease in red color with very large leaf areas. This may be due to such fruit being less exposed to the light owing to the large leaf area. The

reduction in color with the small leaf areas was more marked in appearance than indicated by the table, as the color was usually streaked and a dull brownish red under these conditions. It would seem that at least 20 to 30 leaves per fruit on ringed branches are necessary for normal development of red color in apples. The data indicate that an increase in leaf area above this does not necessarily bring about a further increase in color development but may result in a decrease due to shading. The data indicate that an accumulation of a certain amount of sugar is necessary for the development of a large amount of bright-red color.

TABLE 6.—*Development of red color on surface of apples in relation to leaf area per apple on ringed branches*

Leaves per apple	Percentage of surface having red color						Leaves per apple	Percentage of surface having red color					
	Ben Davis (1925)	Delicious (1925)	York Imperial (1926)	Ben Davis (1926)	Baldwin (1927)	Jonathan (1927)		Ben Davis (1925)	Delicious (1925)	York Imperial (1926)	Ben Davis (1926)	Baldwin (1927)	Jonathan (1927)
0	------	------	------	0	0	3	30	55	44	47	22	26	64
5	21	------	14	22	3	32	50	52	66	49	21	14	66
10	43	33	39	26	7	38	75	41	47	28	20	18	69
20	47	38	43	34	41	40							

That the ground color is also changed by the amount of leaf area per fruit is indicated by the data presented in Table 7. The ground color of the fruit was determined by comparison with a standard chart as described in a previous publication (*30*). A ground color of 1 represents a green color corresponding to that found on very immature apples, and a ground color of 4 is nearly a full yellow with only a slight tinge of green. Ground colors of 2 and 3 are intermediate. The data in Table 7 show a gradual change toward a yellow color with an increase in leaf area up to 30 leaves per fruit. In most cases there is practically no difference in the ground color of apples grown with 50 and with 75 leaves (or with 40 and with 80 leaves in the case of Grimes Golden). As the ground color of apples is an important index to the picking maturity of the fruit, these results indicate that apples grown with a large leaf area might be picked earlier than fruit grown with a small leaf area. That the fruit is actually more mature is probable in view of its higher sugar content and excellent dessert quality.

TABLE 7.—*Ground color of apples on ringed branches in relation to leaf area per apple*

Leaves per apple	Ground color [1]						Leaves per apple	Ground color [1]					
	Grimes Golden (1925)	Delicious (1925)	Ben Davis (1925)	York Imperial (1926)	Baldwin (1927)	Jonathan (1927)		Grimes Golden (1925)	Delicious (1925)	Ben Davis (1925)	York Imperial (1926)	Baldwin (1927)	Jonathan (1927)
0	1.6	------	------	------	1.0	1.7	40	3.8	------	------	------	------	------
5	1.9	------	2.6	2.0	1.4	2.0	50	------	4.0	3.4	2.8	2.3	3.1
10	2.2	2.7	3.0	2.1	1.7	2.2	75	------	4.0	3.6	3.4	2.4	3.1
20	3.3	3.2	3.2	2.0	2.4	2.3	80	3.7	------	------	------	------	------
30	------	3.3	3.3	2.9	2.5	2.8							

[1] Explanation of numbers representing color is given in the paragraph preceding this table.

There were no consistent differences in either ground color or red color in fruit grown on branches that were not ringed, except that fruit grown on branches from which the leaves were all removed usually showed a higher percentage of red color, due to the greater exposure to light. The sugar content of such fruit was usually equal to that of other fruit on unringed branches with a larger leaf area.

RELATION OF DISTANCE AND DIRECTION OF FRUIT FROM LEAVES TO SIZE AND COMPOSITION OF APPLES

In the study of the relation of leaf area to the growth of apples it was found that the size of the fruit increased with an increase in leaf area up to 30 to 50 leaves per fruit even though it was often necessary to use leaves at considerable distance from the fruit to obtain this number of fully developed leaves. It was considered important, therefore, to determine to what extent the fruit could draw elaborated foods from leaves that were various distances away, and to determine the maximum distance from which foods might be transported to the fruit. The results of such an investigation should have a bearing on fruit-bud differentiation and on the practice of thinning. Incidental to this work a study was also made of the increase in size of the fruit in relation to (1) the direction of the leaves from the fruit, (2) the size of the fruit at the beginning of the season, and (3) the seed content of the fruit.

In a preliminary report (*21*) it was found that apples on ringed branches could apparently draw with equal facility upon elaborated foods from leaves 100 cm distant and from leaves adjacent to the fruit. Coit (*12*) showed that there was no significant difference in the size and sugar content of oranges grown on the ends of twigs that were defoliated for 8 inches back and of similar oranges grown on twigs that were not defoliated.

There seems to be no information as to the ability of the fruit to draw upon leaves that are above or below the fruit or that are on separate branches.

Whitehouse (*42*) has found that the size and shape of apples at the beginning of the season are fairly accurate indexes to their size and shape at the end of the season.

RELATION OF LEAF DISTANCE TO GROWTH OF FRUIT

The data on the growth of apples on branches that were not ringed but from which all the leaves had been stripped are presented in Table 8. In the column headed r_{12} are given the correlations between the increase in volume and the distance to the main limb; r_{23} represents the correlation between the volume at the beginning and the distance to the main limb; r_{13} represents the correlation between the increase in volume and the volume at the beginning; and $r_{12.3}$ represents the partial correlation between the increase in volume and the distance to the main limb with the volume at the beginning constant. A correlation that is four times the probable error is considered significant.

TABLE 8.—*Growth of apples on unringed branches from which all the leaves were removed, as shown by correlations between (1) increase in volume of fruit, (2) distance from fruit to main limb, and (3) volume of fruit at the beginning of the experiment*

Variety	Year	Fruits on branch	Distance between apples and main limb	Correlations [1]			
				r_{12}	r_{23}	r_{13}	$r_{12.3}$
		Number	*Cm*				
Ben Davis	1926	21	40–150	+0.088±0.145	+0.041±0.146	+0.831±0.045	+0.096±0.145
York Imperial	1926	25	40–180	−.209± .129	−.293± .123	+.839± .040	+.071± .134
Baldwin	1927	47	50–310	+.449± .078	+.446± .079	+.500± .074	+.292± .090
Do	1927	45	170–475	−.714± .049	−.315± .091	+.595± .065	−.690± .053
Jonathan	1927	55	80–280	+.202± .087	+.499± .068	+.780± .036	−.346± .080
Do	1927	33	60–320	−.033± .117	+.230± .111	+.693± .061	−.275± .108

[1] r_{12} denotes correlation between items 1 and 2; r_{23}, between 2 and 3; r_{13}, between 1 and 3; and $r_{12.3}$, between 1 and 2 with 3 constant, viz: $r_{12.3}=\frac{r_{12}-r_{23}\cdot r_{13}}{\sqrt{1-r_{23}^2}\sqrt{1-r_{13}^2}}$

In 1926 there were used one Ben Davis branch on which were 21 apples that were 40 to 150 cm from the main limb and one York Imperial branch on which were 25 apples 40 to 180 cm from the main limb. In neither case was there a significant correlation between the distance from the leaves or main limb and the increase in the volume of the fruit. (Table 8, r_{12}.)

In 1927 larger branches were used on which some of the fruits were as much as 300 to 475 cm from the main limb. No correlation was found on the two Jonathan branches between the leaf distance and the increase in the volume of the fruit. On the two Baldwin branches the correlation was significant in both cases, being positive, however, in one and negative in the other.

These apparently conflicting results led to a closer study of the data in an effort to determine why a negative correlation was found in one case and a positive correlation in the other. The correlation between the size of the fruit at the beginning of the experiment and the increase in size was calculated to see whether the rate of growth had been changed by stripping the leaves from the branch. The correlations thus obtained (Table 8, r_{13}) were positive and significant in all cases, showing that the relative rate of growth of the different apples had not been greatly changed. Although these results agree with those of Whitehouse (*42*), it is rather surprising to find this relationship maintained even after the removal of all the surrounding leaves.

Since a significant correlation was found between the increase in the size of the fruit and the distance from the main limb without a material change in the relative rate of growth of the fruit, there must have existed a similar correlation between the size of the fruit at the beginning of the experiment and the distance from the main limb. This correlation was computed and is shown in Table 8, r_{23}. On the Baldwin branch in which the correlation between the increase in volume and the distance to the main limb was $+0.449 \pm 0.078$, a correlation of $+0.446 \pm 0.079$ was found to exist at the beginning of the experiment between the size of the fruit and the distance to the main limb, while on the other Baldwin branch correlations of -0.714

± 0.049 and -0.315 ± 0.091, respectively, obtained. Thus the correlations found on the Baldwin branches between the size and the leaf distance appear to be due to a correlation existing before any treatment was given. Therefore, in order to obtain the true effect of the leaf distance on the growth of the apples it was necessary to compute the partial correlation between the increase in size and the distance to the main limb, with the size at the beginning of the experiment constant. This is shown in the column headed $r_{12.3}$.

The corrected results thus obtained show significant negative correlations in the case of one Baldwin branch and one Jonathan branch, while on the other four branches the correlations are not significant. On the Baldwin branch, on which the fruit was 170 to 475 cm from any leaves, a correlation of -0.690 ± 0.053 was obtained. Although this correlation is significant, it is somewhat questionable in view of the fact that a positive correlation of over three times the probable error was obtained on the other Baldwin branch, and also because of the negative correlation already existing at the beginning of the experiment, which may not have been entirely corrected by the use of the partial correlation.

In the case of the Jonathan branches the correlations were negative in both cases and significantly so in one case. This would seem to indicate that in the case of Jonathan as well as Baldwin the extreme distance was becoming a limiting factor in the growth of the fruit. In no case, however, was the reduction in size sufficiently marked to be noticeable by simply looking at the fruit on the branch.

The results on unringed branches indicate that apples can, if necessary, readily obtain elaborated foods from leaves that are at a considerable distance. With the varieties used, no appreciable reduction in size occurred when the leaves were 310 cm distant in the case of Baldwin, about 280 cm in the case of Jonathan, and at least 180 cm and 150 cm in the case of York Imperial and Ben Davis, respectively.

The data on the growth of apples on ringed branches with 1 fruit and 20 leaves at varying distances from the fruit are presented in Table 9. In view of the results obtained on unringed branches, it was deemed advisable to compute the partial correlations between the increase in volume and the leaf distance in order to correct for any correlation that might exist at the beginning of the experiment between the size of the fruit and the leaf distance. This was done, although no significant correlation was found (r_{23}) between the size of the fruit at the beginning and the leaf distance. Neither was there a significant correlation in the case of Grimes Golden between the increase in volume and the volume at the beginning (r_{13}). Contrary to expectations, an apparently significant positive correlation ($r_{12.3}$) was obtained with Grimes Golden in the first year of the experiment (1925). This would indicate that the farther the apples were from the leaves up to 110 cm the larger they would become, which seemed obviously incorrect. It was somewhat difficult to find branches on which the fruit could be separated widely from the leaves; consequently the larger and longer the branch the farther the fruit was likely to be separated from the leaves, while small branches were used where the leaves were adjacent to the fruit. The explanation for the positive correlation obtained the first year is probably that the large branches with the more distantly separated fruit and leaves

were less injured by the ringing operation than were the small branches. In the later experiments an effort was made to use branches of the same size for the small distances as for the large. The first year's results indicated that at least there was no decrease in the size of the fruit even though there were no leaves within 100 cm of the fruit.

TABLE 9.—*Growth of apples on ringed branches with 1 fruit and 20 leaves, as shown by correlations between (1) increase in volume of fruit, (2) distance from fruit to leaves, and (3) volume of fruit at the beginning of the experiment*

Variety	Year	Branches	Distance between apples and leaves	Correlations [1]			
				r_{12}	r_{23}	r_{13}	$r_{12.3}$
		Number	*Cm*				
Grimes Golden	1925	125	0–110	+0.519±0.044	+0.129±0.059	+0.131±0.059	+0.511±0.045
Do	1926	70	0–135	+.265± .075	+.176± .078	+.117± .079	+.289± .074
Ben Davis	1926	63	0–180	−.092± .084	−.158± .084	+.904± .016	+.121± .084
Baldwin	1927	71	0–200	+.036± .107	−.204± .081	+.672± .058	+.194± .077
Jonathan	1927	43	0–240	−.482± .079	−.106± .102	+.405± .086	−.483± .080
Do	1927	35	0–170	−.038± .114	+.054± .114	+.318± .102	−.058± .114

[1] For explanation see footnote to Table 8.

The experiment was repeated in 1926 with the Grimes Golden and Ben Davis varieties and in 1927 with Baldwin and Jonathan. Again in 1926 the corrected correlation ($r_{12.3}$) for Grimes Golden was positive and practically significant, being 3.9 times the probable error. In this case the correlation was not due to differences in the size of the branches, as an effort was made to use as large branches for the short as for the long distances. The circumference of the branch at the ring was measured in each case, and the correlation between the circumference of the branches and the increase in the volume of the fruit was $+0.064 \pm 0.12$, showing that the size of the branches had not affected the growth of the fruit.

In the case of Ben Davis and Baldwin the correlations ($r_{12.3}$) were not significant. In the Jonathan variety, in which the leaves were in some cases as much as 240 cm from the fruit, a significant negative correlation was obtained. When the branches on which the leaves were more than 170 cm from the fruit were left out, the correlation was $r = -0.059 \pm 0.114$, indicating that the distance was not a limiting factor up to 170 cm.

In general, the results on ringed branches indicate that, if necessary, apples can secure food materials with equal facility from leaves that are a considerable distance away and from those that are immediately adjacent. With Grimes Golden, there was no decrease in the growth of the apples up to 135 cm, with Ben Davis up to 180 cm, with Baldwin up to 200 cm, and with Jonathan up to at least 170 cm.

Although the foregoing results show that an apple will grow as large with 20 leaves that are at a considerable distance as will an apple with 20 leaves immediately adjacent, it was thought that the distant fruit might not be able to grow so large if two apples, one of which was distant, were competing for elaborated foods from the same leaves. To determine this point, branches were ringed with 20 leaves and 2 apples above the ring, one of the apples being adjacent to the leaves and the other at a considerable distance from them. (Fig. 1, D.) The data for this experiment are presented in Table 10.

TABLE 10.—*Growth of apples on ringed branches in relation to distance of fruit from leaves*

[Branches with 20 leaves and 2 apples]

Variety and year	Distance from leaves	Volume at start		Increase in volume		Relative increase in volume / Relative volume at start
		Average	Relative	Average	Relative	
		Cm³	*Per cent*	*Cm³*	*Per cent*	
Jonathan, 1927	Adjacent	42.1	100	71.8	100	
Do	Distant (112 cm)	43.1	102.4	61.5	85.7	83.7 per cent.
Baldwin, 1927	Adjacent	44.4	100	144.0	100	
Do	Distant (109 cm)	38.9	87.6	96.7	67.2	76.7 per cent.

In the case of the Jonathan variety seven branches with the distant apples averaging 112.4 cm from the leaves were treated in this way. In the Baldwin variety 15 branches with the distant apples averaging 109.2 cm from the leaves were treated. At the beginning of the experiment the distant apples averaged slightly larger (2.4 per cent) than those adjacent to the leaves in the case of the Jonathan variety, while with the Baldwin variety the distant apples were considerably smaller (12.4 per cent). In both cases the increase in the size of the distant apples was less than that of those adjacent to the leaves, being 85.7 per cent as great in the case of Jonathan and 67.2 per cent in the case of Baldwin. Since it was found in the previous experiments that the increase in volume was correlated with the volume at the beginning of the experiment, it would have been expected that the distant Baldwin apples would have increased in volume only 87.6 per cent as much as the apples close to the leaves if they were able to draw with equal facility upon the leaves. Since the distant fruit grew only 67.2 per cent, it appears that while they were able to obtain considerable elaborated foods from the leaves, they were not able to get as much as the adjacent fruit. The last column of Table 10 shows the amount of growth they made relative to the amount of growth they would have been expected to make from their relative volume at the start of the experiment, and shows that the rate of growth of the distant apples was decreased to 83.7 per cent in the case of Jonathan and 76.7 per cent in the case of Baldwin. Thus the distant apples apparently received respectively 83.7 and 76.7 per cent as much of the elaborated foods as did the apples adjacent to the leaves.

RELATION OF DIRECTION OF APPLES FROM LEAVES TO GROWTH OF FRUIT

In the experiment in which branches were ringed and 1 fruit and 20 leaves left above the ring at varying distances from the fruit, the leaves were in some cases above the fruit, as in Figure 1, B, and in other cases they were below the fruit or on separated branches, as in Figure 1, C. In order to determine whether the direction of the fruit from the leaves had any effect on its ability to draw on the elaborated foods, the average increase in the size of the fruit in the various positions was determined and is shown in Table 11. When the growth of the apples with the leaves adjacent was used as a standard, it was found that in no case was there a significant difference in the increase in the volume of the fruit whether the leaves were below the fruit, above the fruit, or on separate branches.

TABLE 11.—*Growth of apples on ringed branches in relation to relative position of leaves and fruit*

Variety	Year	With leaves adjacent to fruit		With leaves below fruit		With leaves above fruit		With leaves on separate branch	
		Apples	Increase in volume	Apples	Increase in volume	Apples	Increase in volume	Apples	Increase in volume
		Number	*Cm³*	*Number*	*Cm³*	*Number*	*Cm³*	*Number*	*Cm³*
Grimes Golden	1926	14	68.6±2.7	13	72.1±2.7	28	78.6±1.3	15	71.8±2.1
Ben Davis	1926	14	100.7±2.9	7	93.9±2.9	30	97.2±1.8	11	107.0±4.2
Baldwin	1927	11	165.0±2.4	2	170.5	14	167.9±5.5	13	168.1±5.1
Jonathan	1927	10	98.0±1.8			13	99.8±1.8	20	93.2±2.8

RELATION BETWEEN NUMBER OF SEEDS PER APPLE AND SIZE OF FRUIT

In the experiments herein reported it was found that there was some variation in the increase in the size of the fruit even though it was grown with the same number of leaves. This variation was not correlated with the distance from the leaves but seemed to depend on the size of the fruit at the beginning of the experiment. In view of the results obtained by Morris (*34*), Auchter (*4*), Asami (*2*), and others, it was thought that the variation in the size of the fruit at the beginning of the experiment might be due to the number of seeds per fruit. At the time of sampling the fruit for chemical analysis the seeds in each apple were counted and the number correlated with the size of the fruit at the beginning of the experiment. The results are presented in Table 12. Slight positive correlations were obtained in the case of York Imperial and Jonathan. In the case of the former, however, the correlation is not significant, owing to the high probable error. While the number of seeds per apple may be partly responsible for the variation in the size of the Jonathan apples, it apparently had little effect on the growth of the fruit in the other varieties studied.

TABLE 12.—*Correlation between number of seeds and volume of apples at the beginning of the experiment*

Variety	Year	Fruits	Seeds per fruit	Correlation between number of seeds and volume of fruit
		Number	*Number*	
Ben Davis	1926	57	3 to 10	+0.111±0.088
York Imperial	1926	52	4 to 10	+.298± .085
Jonathan	1927	259	1 to 10	+.229± .040
Baldwin	1927	186	1 to 7	−.002± .049

RELATION BETWEEN LEAF DISTANCE AND CHEMICAL COMPOSITION OF FRUIT

Following harvest, the apples from each of the experiments were arbitrarily grouped according to their distance from the leaves, and analyses for sugars and acid were then made on each group. For the fruit from ringed branches the results are presented in Table 13 and Figure 6, and for the branches that were not ringed but from which all the leaves had been stripped the results are shown in Table 14 and Figure 7.

TABLE 13.—*Relation between leaf distance and chemical composition of fruit on ringed branches each with 1 fruit and 20 leaves above ring*

Variety and year	Group [1]	Average leaf distance	Average increase in volume	Sugars (percentage of fresh weight)			Acid as malic (percentage of fresh weight)
				Reducing, as dextrose	Sucrose, as dextrose	Total, as dextrose	
		Cm	*Cm*³				
Ben Davis, 1926	a	10	100.5	7.7	1.8	9.5	0.30
	b	40	112.2	7.9	1.6	9.5	.28
	c	70	90.7	7.5	1.5	9.0	.28
	d	90	103.6	7.6	1.8	9.4	.28
	e	113	94.0	7.5	1.4	8.9	.28
	f	169	99.8	7.2	2.2	9.4	.32
Jonathan, 1927	a	10	97.7	9.8	2.1	11.9	.52
	b	86	101.6	10.4	1.8	12.2	.50
	c	144	97.2	9.7	1.9	11.6	.57
	d	208	79.4	9.6	1.1	10.7	.47
Baldwin, 1927	a	11	165.2	8.4	3.1	11.5	.47
	b	80	160.9	8.4	3.6	12.0	.48
	c	133	167.2	8.2	4.5	12.7	.52
	[2] A	12	144.0	8.2	2.6	10.8	.45
	[2] B	109	96.7	8.2	1.4	9.6	.43

[1] Groups represent fruits grown in the same range of distances from the leaves.
[2] Branches with 20 leaves and 2 apples: A, Adjacent to leaves; B, distance from leaves.

TABLE 14.—*Relation between leaf distance and chemical composition of fruit on unringed branches from which all leaves were stripped*

Variety and year	Branch No.	Group [1]	Average leaf distance	Average increase in volume	Sugars (percentage of fresh weight)			Acid as malic (percentage of fresh weight)
					Reducing	Sucrose	Total	
			Cm	*Cm*³				
York Imperial, 1926	J-5	a	51	63.9	9.0	1.4	10.4	0.38
	J-5	b	67	57.9	9.0	1.0	10.0	.38
	J-5	c	90	64.5	9.1	1.1	10.2	.39
	J-5	d	124	56.9	8.9	1.2	10.1	.40
	J-5	e	176	54.1	8.6	.8	9.4	.43
Ben Davis, 1926	J-4	a	57	59.3	7.3	.6	7.9	----------
	J-4	b	84	64.0	7.4	.6	8.0	.31
	J-4	c	100	69.4	7.4	.5	7.9	.29
	J-4	d	138	57.3	7.5	1.2	8.7	.29
Jonathan, 1927	J-1	a	114	67.0	9.5	1.2	10.7	.57
	J-1	b	176	71.3	9.7	1.1	10.8	.55
	J-1	c	229	72.0	10.0	1.0	11.0	.60
	J-2	a	166	70.8	9.7	.8	10.5	.51
	J-2	b	271	71.2	9.7	.7	10.4	.48
Baldwin, 1927	J-2	a	133	109.8	7.5	1.9	9.4	.61
	J-2	b	205	112.6	7.5	1.9	9.4	.61
	J-2	c	249	130.8	8.0	1.1	9.1	.61
	J-5	a	233	140.2	8.0	2.5	10.5	.52
	J-5	b	351	124.9	7.6	3.1	10.7	.47
	J-5	c	443	107.0	8.1	2.9	11.0	.48

[1] Groups represent fruits grown in the same range of distances from the leaves.

In no case was there a consistent or significant variation in the acid content. There was practically no variation in the sugar content of Ben Davis apples from ringed branches whether near to or far from leaves. (Table 13.) In the case of Jonathan there was a decrease in sucrose and total sugars in the most distant group, associated with a decrease in the size of the fruit. In the case of Baldwin, however, there was an increase in sucrose and total sugars with an increase in the distance between the fruit and the leaves. Groups A and B under Baldwin (Table 13) represent apples from ringed branches on

which there were 20 leaves and 2 apples, one of which (A) was adjacent to the leaves and the other (B) distant from the leaves. (Fig. 1, D.) In this case the apples in the B group averaged much smaller than those in the A group and also showed a lower sucrose and total sugar content.

There was very little variation in the sugar content of the apples from the branches that were not ringed but from which the leaves had been stripped. (Table 14.) In general, a decrease or an increase in total sugar content seems to be associated to some extent with a corresponding decrease or increase in the volume of the fruit on ringed branches (fig. 6) rather than with the distance between the fruit and the leaves. Fruit on unringed branches, however, does not seem to show this relation. (Fig. 7.) In all cases the differences are slight.

RELATION OF LEAF AREA PER APPLE TO BUD DIFFERENTIATION

It has been shown previously that apples require a rather large leaf area of 30 or more leaves per fruit for the development of good size and quality. Since a fruiting spur usually does not have nearly so many leaves as this, it is necessary for the fruit to draw upon other leaves. This it can do to a considerable degree. It would seem, therefore, that when trees are producing a heavy crop the fruit might utilize nearly all of the material synthesized not only in the fruit-bearing spurs but also in spurs and twigs at considerable distances from them, so that a condition of high carbohydrate concentration apparently necessary for the formation of blossom buds would not exist in the spurs. That heavy fruit production inhibits blossom-bud formation is well recognized. Theoretically, by thinning the fruit previous to bud differentiation it should be possible to reduce the carbohydrate consumption by the fruit to such an extent that there would be sufficient accumulation of carbohydrates in the spurs to bring about conditions favorable to blossom-bud differentiation. It is probable, however, that there would be little accumulation of carbohydrates in the spurs until not only the major requirements of the fruit but also the major requirements for the growth of the tree as a whole have been met.

REVIEW OF PREVIOUS WORK

Thompson (*41*) found an average increase in dry weight for two trees each of five varieties of 39.7 pounds in growth of leaves, branches, trunk, and roots during the ninth year. In a more mature tree this figure would be much larger if the tree were making a good vegetative growth. On the other hand, a 400-pound crop of apples with a dry weight of 15 per cent of the fresh weight would require 60 pounds of dry matter. It seems reasonable to suppose, therefore, that the dry weight added to the tree in the growth of leaves, shoots, and roots, and increase in girth of trunk and limbs, would almost equal the dry weight of a fairly heavy crop of fruit, provided the tree is in a thrifty, growing condition.

Since the work of Kraus and Kraybill (*26*) with the tomato, considerable attention has been given by horticulturists to the relation of the carbohydrate-nitrogen ratio to blossom-bud differentiation in

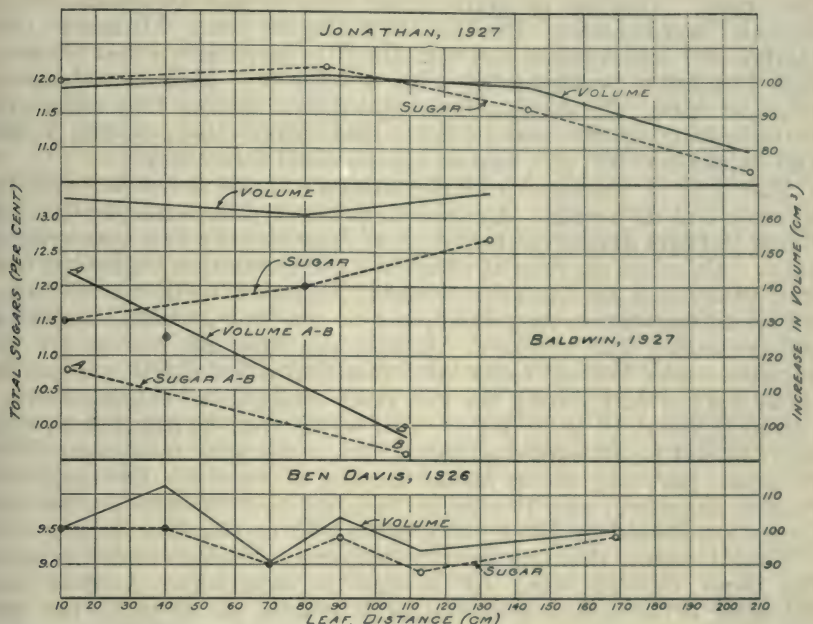


FIGURE 6.—Effect of leaf distance on size and composition of apples on ringed branches. (A and B refer to apples grown on the same branch with 20 leaves, A being adjacent to and B distant from the leaves)

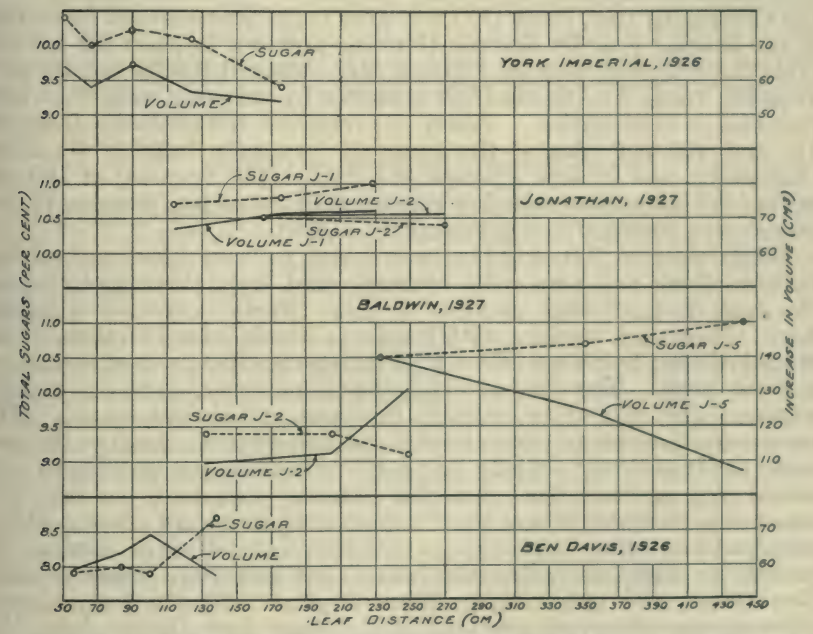


FIGURE 7.—Effect of leaf distance on size and composition of apples on unringed branches. (J-2 and J-5 refer to branch numbers as given in Table 14)

the apple. Analyses of spurs at the time of bud differentiation by various investigators—Hooker (*24*), Harvey and Murneek (*23*), Harley (*22*), and Auchter and Schrader (*6*)—have shown that blossom-bud formation is associated with a relatively high carbohydrate-nitrogen ratio. It also has been shown that factors that reduce the carbohydrate supply, such as heavy fruit production, shading (*7*, *20*), and defoliation (*27*, *40*), inhibit blossom-bud formation.

The time of blossom-bud differentiation varies somewhat with the location and the season. In general, however, differentiation has been found to begin during the last week of June and the first two weeks of July. Although the time at which bud differentiation begins has been well established, the literature does not clearly define the period during which differentiation may take place or the time at which maximum differentiation has occurred. Rasmussen (*39*) has shown for two varieties under Pennsylvania conditions that differentiation began the latter part of July during the two years studied and extended over a period of about 10 to 20 days. This would seem to indicate a rather short period for blossom-bud formation. Normally maximum differentiation probably occurs before the first of August. For maximum results, therefore, any treatment designed to influence blossom-bud formation should be given early enough to be effective during July.

That blossom thinning greatly influences blossom-bud formation has been demonstrated by several investigators. Auchter and Schrader (*6*) obtained blossom-bud formation on 32 to 37 per cent of the spurs from which the blossoms were removed, as compared with 1 per cent of the spurs that matured fruit and 50 per cent of the nonblossoming spurs. This work was done on a Stayman Winesap tree which was apparently bearing annually. With a biennially bearing Oldenburg tree, Crow (*13*) was able to get blossom-bud formation in the bearing year by blossom thinning previous to petal fall but not after the fruit was well set. Drain (*17*) obtained similar results with Wealthy trees, but thinned his blossoms by spraying with chemicals previous to fertilization. Bailey (*8*) removed the blossoms from 50, 75, and 100 per cent of the spurs of biennially bearing Wealthy, Oldenburg, and Yellow Transparent trees. The removal of 100 per cent of the blossoms resulted in blossom-bud formation, whereas 75 and 50 per cent removal had practically no effect.

While blossom thinning has been found to favor blossom-bud formation, there has been little evidence that fruit thinning following the June drop, or even previous to that, affects blossom-bud formation. Beach (*9*), working with Baldwin, Rhode Island Greening, and Hubbardston, found no effect of thinning on blossom-bud formation in New York. The time at which the thinning was done was usually between July 1 and 15, though this was not always stated. The maximum distance to which he thinned was 6 inches, and the thinned trees produced only slightly less total crop than the unthinned. It would appear, therefore, that the thinning was done too late and was not sufficiently severe to be expected to have any effect on blossom-bud formation. Auchter (*3*, *4*) studied the effect of thinning on several varieties, including Baldwin, York Imperial, Rome Beauty, Ben Davis, and Delicious, in West Virginia. He thinned at three different periods—just previous to the June drop (about June 15), just after the June drop (about July 1), and in midsummer (August 15). The maximum distance the fruit was thinned was 9 to 10

inches. The thinning in most cases did not materially reduce the total crop per tree, nor did it have any effect on blossom-bud formation.

Auchter and Schrader (*6*) obtained blossom-bud formation on 5 per cent of the spurs from which the fruit was thinned at the time of the June drop, as compared with 1 per cent of the spurs that matured fruit. Auchter and Whitehouse [4] showed that complete removal of the fruit from the entire tree or from half of a tree resulted in blossom-bud differentiation and successive blossoming. Magness and Overley (*31*), reporting on investigations similar to those presented herein, showed an increase in blossom-bud formation with an increase in leaf area on ringed branches under conditions in Washington State.

Aldrich (*1*) thinned several varieties of biennially bearing trees to 50 and 100 leaves per apple. He found that the thinning of vigorous trees, if sufficiently heavy, usually resulted in increased blossom-bud formation, even if the thinning was done as late as July 1.

From the investigations reviewed above it would seem that blossom-bud formation is normally associated with an accumulation of carbohydrates in spurs sufficient to give a fairly high carbohydrate-nitrogen ratio, and that heavy fruit production prevents this. The thinning investigations have shown that reduction of fruiting by blossom thinning may bring about blossom-bud formation, but that fruit thinning as usually practiced does not. From this it has been concluded by some that the critical period for blossom-bud differentiation is at or immediately following blossoming. In most fruit-thinning investigations, however, the thinning has been done about the time of the initiation of bud differentiation, which may not be early enough to allow any material carbohydrate accumulation before much of the differentiation is complete. Furthermore, since most thinning has not been so severe as to reduce materially the total crop, and since it must require as much carbohydrate to produce a given weight of fruit, whether the fruits are large or small, it is difficult to see how such thinning could be of much benefit to the carbohydrate accumulation of the tree as a whole.

RESULTS OF PRESENT INVESTIGATIONS

The data on the bud counts in 1926 following the treatments given in 1925 are presented in Table 15; those for 1927 following treatment in 1926 are presented in Table 16, and those for 1928 following treatment in 1927 in Table 17. The results are shown graphically in Figure 8.

In 1925 treatments were applied to three varieties—Grimes Golden, Delicious, and Ben Davis. Of these varieties, Grimes Golden and Ben Davis are normally regular annual bearers, and Delicious under some conditions tends to alternate. During this year the number of leaves per apple on the unringed branches was the same previous to the date of treatment as after, since neither leaves nor fruit were removed from such branches at the beginning of the experiment. As the fruiting spurs were not labeled, it was sometimes difficult at the time the bud counts were made to distinguish between those that had fruited and those that had only blossomed in the year previous.

[4] AUCHTER, E. C., and WHITEHOUSE, W. E. Unpublished data. Maryland Agricultural Experiment Station. 1926.

It will be seen from Table 15 and Figure 8 that on ringed branches variations in the leaf area per apple had a decided effect on the formation of blossom buds. In general, with 10 or less leaves per apple, blossom-bud formation was inhibited in all varieties; with 20 leaves per apple slight to moderate blossom-bud formation occurred; and with 30 or more leaves per apple a large percentage of blossom buds were formed even on spurs that bore fruit the previous season. Treatments given as late as June 17 and 18 on Grimes Golden greatly influenced the formation of blossom buds.

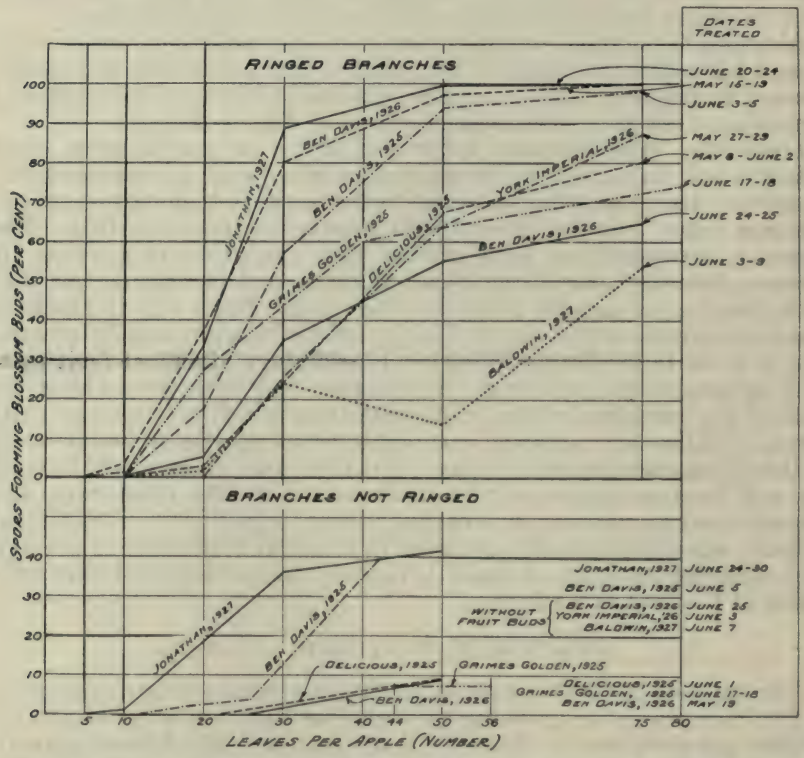


FIGURE 8.—Effect of leaf area per apple on blossom-bud formation on ringed and unringed branches

On unringed branches there was an increased formation of blossom buds with increased leaf area, with the exception of Grimes Golden, in which no branches were used with small leaf areas per apple.

In 1926 two varieties were used—Ben Davis, which is normally regular in bearing but in this case was bearing biennially, and York Imperial, which tends to bear alternately and was doing so in this case. One Ben Davis tree was treated between May 15 and 19 and another was treated June 24 and 25. When bud counts were made in 1927 there were no fruit buds on either the York Imperial or the Ben Davis trees except on some of the branches that were treated, as recorded in Table 16.

TABLE 15.—*Effect of leaf area per apple on blossom-bud formation (bud counts made in 1926 following treatments in 1925)*

[Branches ringed except as noted]

Variety	Date of treatment	Leaves per apple (1925)	Leaf spurs of 1925		Blossoming spurs of 1925			Fruiting spurs of 1925			All spurs of 1925		
			Leaf buds (1926)	Blossom buds (1926)	Leaf buds (1926)	Blossom buds (1926)		Leaf buds (1926)	Blossom buds (1926)		Leaf buds (1926)	Blossom buds (1926)	
			No.	*No.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*
Grimes Golden.	June 17–18	80	89	288	17	75	81.5	24	13	35.1	130	376	74.3
	do	40	64	131	22	29	56.9	23	7	23.3	109	167	60.5
	do	20	64	26	19	15	44.1	25	0	0	108	41	27.5
	do	10	51	0	12	1	7.7	24	0	0	87	1	1.1
	do	5	21	0	3	0	0	27	0	0	51	0	0
	do.[1]	56	121	12	25	2	7.4	21	0	0	167	14	7.7
	do.[1]	44	192	19	21	1	4.5	31	0	0	244	20	7.6
Delicious	May 8 to June 2	75	88	327	7	51	87.9	3	29	90.6	98	407	80.6
	May 9 to June 2	50	87	166	10	33	76.7	10	21	67.7	107	220	67.3
	do	30	122	42	19	4	17.3	28	9	24.3	169	55	24.5
	May 27 to June 2	20	117	5	29	0	0	43	1	2.3	189	6	3.1
	May 29 to June 2	10	73	0	26	0	0	42	0	0	141	0	0
	May 29 to June 3	5	34	0	10	0	0	33	0	0	77	0	0
	June 1 [1]	50	245	29	15	1	6.3	29	0	0	289	30	9.4
	do.[1]	22	58	0	17	0	0	14	0	0	89	0	0
Ben Davis	June 3	75	6	243	0	25	100	0	24	100	6	292	98.0
	June 4	50	10	150	0	7	100	2	27	93	12	184	93.9
	do	30	26	47	4	3	42.8	15	9	37.5	45	59	56.7
	do	20	56	13	8	3	27.3	21	1	4.5	85	17	16.7
	June 5	10	39	0	1	0	0	22	0	0	62	0	0
	do	5	29	0	8	0	0	26	0	0	63	0	0
	do.[1]	42	127	97	9	7	43.8	34	5	12.8	170	109	39.1
	do.[1]	26	76	5	32	1	3.0	26	0	0	134	6	4.3
	do.[1]	17	13	0	12	1	7.7	24	0	0	49	1	2.0
	do.[1]	12	6	0	1	0	0	11	0	0	18	0	0

[1] Unringed branch.

On ringed branches a higher percentage of blossom buds formed on the Ben Davis tree treated in May than on the one treated in June. Only 10 leaves per apple were necessary for the formation of blossom buds on the ringed branches of the Ben Davis tree treated in May, whereas 30 leaves per apple were necessary on the York Imperial tree treated about 10 days later.

No blossom buds were formed on unringed branches of York Imperial or Ben Davis except on the Ben Davis branch thinned to 50 leaves per apple in May.

In 1927 two varieties were used—Jonathan, which was bearing regularly, and Baldwin, which tends to bear alternately and was doing so in this case.

On ringed branches (Table 17) 20 leaves per apple caused over a third of the spurs to form blossom buds, and practically all spurs formed blossom buds with 50 or 75 leaves per apple in the case of Jonathan, whereas with Baldwin 30 leaves were necessary for the formation of blossom buds on 25 per cent of the spurs, and 75 leaves resulted in blossom buds on only 53 per cent of the spurs.

On unringed Jonathan branches there was an increased blossom-bud formation with increased leaf area per fruit, whereas with Baldwin no blossom buds were formed on any of the unringed branches, even though all the fruit was removed from one of the branches. This branch was over 3 inches in diameter at the base and about 25 feet long, so that it was thought that it would act to a large extent independently of the rest of the tree.

TABLE 16.—*Effect of leaf area per apple on blossom-bud formation (bud counts made in 1927 following treatments in 1926)*

[Branches ringed except as noted]

Variety	Date of treatment	Leaves per apple		Leaf spurs of 1926			Blossoming spurs of 1926			Fruiting spurs of 1926			All spurs of 1926		
		Before treatment	After treatment	Leaf buds (1927)	Blossom buds (1927)		Leaf buds (1927)	Blossom buds (1927)		Leaf buds (1927)	Blossom buds (1927)		Leaf buds (1927)	Blossom buds (1927)	
				No.	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*
Ben Davis	May 15	----	75	0	109	100	0	72	100	0	10	100	0	191	100
	May 17	----	50	2	102	98.1	2	39	95.1	1	14	93.3	5	155	96.9
	May 18	----	30	17	77	81.9	5	20	80.0	5	11	68.7	27	108	80.0
	----do	----	20	49	35	41.7	24	10	29.4	14	8	36.4	87	53	37.9
	May 19	----	10	39	1	2.5	24	1	4.0	20	1	4.8	83	3	3.5
	----do	----	5	8	0	0	16	0	0	15	0	0	38	0	0
	June 24	----	75	38	40	51.3	9	50	84.7	5	5	50.0	52	95	64.6
	----do	----	50	24	17	41.5	7	27	79.4	6	1	14.3	37	45	54.9
	June 25	----	30	16	14	46.7	15	8	34.8	10	0	0	41	22	34.9
	----do	----	20	37	0	0	22	4	15.4	10	0	0	69	4	5.5
	----do	----	10	24	0	0	6	0	0	8	0	0	38	0	0
	----do	----	5	5	0	0	20	0	0	12	0	0	37	0	0
	May 19 [1]	----	50	145	9	5.8	102	17	14.3	27	1	3.6	274	27	9.0
	----do.[1]	----	25	30	0	0	61	0	0	15	0	0	114	0	0
	----do.[1]	----	6	24	0	0	30	0	0	56	0	0	110	0	0
	June 25 [1]	11	51	39	0	0	39	0	0	13	0	0	91	0	0
	----do.[1]	20	30	59	0	0	42	0	0	20	0	0	121	0	0
	----do.[1]	10	20	22	0	0	64	0	0	22	0	0	108	0	0
	----do.[1]	11	10	26	0	0	9	0	0	24	0	0	59	0	0
	----do.[1]	11	0	50	0	0	17	0	0	19	0	0	86	0	0
York Imperial	May 27–28	----	75	47	363	88.5	5	71	93.4	11	6	35.3	63	440	87.5
	May 28	----	50	92	134	59.3	12	59	83.1	8	5	38.5	112	198	63.9
	May 28–29	----	30	110	28	20.3	50	30	37.5	13	2	13.3	173	60	25.8
	May 29	----	20	75	0	0	72	0	0	25	0	0	172	0	0
	----do	----	10	66	0	0	38	0	0	23	0	0	127	0	0
	May 29 to June 1	----	5	66	0	0	62	0	0	19	0	0	147	0	0
	June 3 [1]	48	50	----	0	0	----	0	0	----	0	0	----	0	0
	----do.[1]	34	30	----	0	0	----	0	0	----	0	0	----	0	0
	----do.[1]	16	20	----	0	0	----	0	0	----	0	0	----	0	0
	----do.[1]	20	10	----	0	0	----	0	0	----	0	0	----	0	0
	----do.[1]	----	0	----	0	0	----	0	0	----	0	0	----	0	0

[1] Unringed branch.

It is of particular interest to note that in the case of the two varieties that tend to bear alternately, York Imperial and Baldwin, practically no blossom-bud formation occurred with 20 leaves per fruit on ringed branches, whereas with Jonathan, Ben Davis, and Grimes Golden, which are normally annual bearers, fairly good blossom-bud formation occurred with 20 leaves. Blossom-bud formation in Delicious, which tends to bear alternately but not to so great an extent as York Imperial and Baldwin, was low with 20 leaves per apple. This would seem to indicate that varieties that tend to bear alternately require a higher leaf area per apple for the development of blossom buds.

While analyses of the spurs were not made, the analyses of the fruit should be to some extent an index to the concentration of sugars in the spurs. The concentration of sugars in the spurs would be expected to be proportional to that in the fruit. In this connection it is of interest to note (Table 4) that the concentration of total sugars in apples on unringed branches that failed to form blossom buds was lower than the concentration of sugars in fruit on ringed branches that formed blossom buds. In the case of Baldwin, for example, 30 leaves per apple on ringed branches were required to form

TABLE 17.—*Effect of leaf area per apple on blossom-bud formation (bud counts made in 1928 following treatments in 1927)*

[Branches ringed except as noted]

Variety	Date of treatment	Leaves per apple (1927)	Leaf spurs of 1927		Blossoming spurs of 1927			Fruiting spurs of 1927			All spurs of 1927		
			Leaf buds (1928)	Blossom buds (1928)	Leaf buds (1928)	Blossom buds (1928)		Leaf buds (1928)	Blossom buds (1928)		Leaf buds (1928)	Blossom buds (1928)	
			No.	*No.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*
Jonathan	June 20–22	75	1	260	0	190	100	0	20	100	1	470	99. 8
	June 21–22	50	0	143	0	116	99. 1	1	20	95. 2	2	279	99. 7
	do	30	5	75	7	100	93. 5	11	15	57. 7	23	190	89. 2
	do	20	49	27	31	20	45. 6	22	1	4. 3	102	54	34. 6
	June 22–23	10	75	0	76	0	0	14	0	0	165	0	0
	June 23–24	5	84	0	52	0	0	23	0	0	159	0	0
	June 24	0	54	0	72	0	0	20	0	0	146	0	0
	June 25 [1]	50	14	22	16	29	64. 4	7	1	12. 5	52	37	41. 6
	do.[1]	30	13	16	31	18	36. 7	16	0	0	60	34	36. 2
	do.[1]	10	19	0	53	1	1. 9	13	0	0	85	1	1. 2
	June 24 [1]	0	75	0	156	0	0	46	0	0	277	0	0
	June 30 [1]	0	131	0	110	0	0	25	0	0	266	0	0
Baldwin	June 3–8	75	75	126	42	19	31. 1	10	2	16. 7	127	147	53. 6
	June 3–9	50	80	13	3	1	25. 0	7	0	0	90	14	13. 5
	June 6–9	30	75	26	2	0	0	8	1	11. 1	85	27	24. 1
	do	20	124	3	23	0	0	26	0	0	173	3	1. 7
	June 7–9	10	55	0	29	0	0	25	0	0	109	0	0
	do	5	28	0	15	0	0	24	0	0	67	0	0
	June 7 [1]	[2]	-----	0	-----	0	0	-----	0	0	-----	0	0
	do.[1]	50	7	0	13	0	0	37	0	0	57	0	0
	do.[1]	8	18	0	0	0	0	11	0	0	29	0	0
	do.[1]	0	27	0	0	0	0	40	0	0	67	0	0
	do.[1]	0	34	0	0	0	0	29	0	0	63	0	0

[1] Unringed branch.

[2] Apples removed.

blossom buds and the fruit had a total sugar concentration of 12.8 per cent; fruit on the unringed branches had a sugar concentration of only 10 to 11 per cent and failed to form blossom buds. Similarly, York Imperial formed blossom buds on ringed branches with 30 leaves per fruit with a total sugar concentration of 12.7 per cent in the fruit; no blossom buds were formed on the unringed branches, and the total sugar concentration in the fruit in all cases was less than 12 per cent. In the case of Jonathan, blossom buds were formed on ringed branches with 20 leaves per fruit and a sugar concentration of 11.6 per cent. On the two unringed branches, in which the fruit had a similar sugar concentration of 11.6 and 11.8 per cent, blossom buds were formed to practically the same extent as on the ringed branches with 20 leaves per fruit, whereas practically no blossom buds were formed on the other unringed branches in which the sugar concentration of the fruit was less than 11.6 per cent. A similar relation obtained in the other varieties studied.

DISCUSSION

Varying the leaf area per apple on ringed branches greatly influenced the size and quality of the fruit, whereas similar treatment on branches that were not ringed had relatively much less effect on the fruit. The question arises, then, which of these treatments more nearly represents what would happen if entire trees were treated in a similar manner? When individual branches are treated without ringing there seems to be a translocation of food materials away from

or to the branch, depending on whether there are more or fewer leaves per apple on the branch than on the tree as a whole. If an entire tree were treated so that there was a very small leaf area per apple, there would be no other source of elaborated food supply to draw upon, except possibly reserve or storage materials that might be present in the branches, trunk, and roots; so that under conditions of small leaf area the fruit probably would respond as on ringed branches. Thus, Auchter (*4*) found that when practically all of the leaves dropped early in the summer because of cedar rust, the fruit ceased to develop and became no larger than walnuts. On the other hand, in case an entire tree were thinned so that there was a very large leaf area per apple, there would probably be considerable translocation of elaborated foods away from the fruit to the trunk and roots. In the latter case a large leaf area per fruit on an entire tree would not have so great an effect on the fruit as it would on ringed branches. It probably would have a much greater effect, however, than a similar large leaf area per fruit on an unringed branch, since the roots probably would not draw upon the synthesized foods to the same extent as fruit on adjacent branches with a smaller leaf area.

The evidence presented seems to indicate that with a limited supply of elaborated foods the fruit may utilize the available material to a greater extent than other parts of the plant. This is brought out by the fact that fruit grown at a considerable distance from any leaves became practically as large as fruit grown adjacent to leaves and its sugar and acid content was not materially changed. For example, fruit on unringed branches from which all the leaves were removed grew as large as, and in most cases larger than, similar fruit on ringed branches with 10 leaves per fruit. Thus, in the case of Baldwin in 1927, there were, respectively, 47 and 45 apples on each of the two branches used. (Table 8.) Since each apple apparently used at least as much food as was elaborated in 10 leaves, the amount of food translocated into each of the branches must have been as much as was elaborated by 470 and 450 leaves, respectively. This amount of food was translocated a distance of 50 to 310 cm in one case and 170 to 475 cm in the other. A further indication that the fruit tends to monopolize the available synthesized foods is that the principal movement seems to be in the direction of the fruit, and may be either upward or downward or from one branch to another, depending on whether the fruit is above the leaves, below the leaves, or on a separate branch.

In this connection, Murneek (*35*) found that vegetative growth in the tomato was inhibited by the development of the fruit and was associated with an accumulation of carbohydrates and nitrogen in the fruit. The accumulation of nitrogen, however, was thought to be the factor responsible for the decreased vegetative growth. Similar results were also found for the apple (*36*, *37*), in which both nitrogen and carbohydrate material accumulated in the fruit to a much greater extent than in any other part of the bearing spur system.

It would seem therefore that the fruit requires a large amount of synthesized food for proper development, and that there would be little available for vegetative growth and the development of buds unless there is sufficient leaf area to more than supply the major requirements of the fruit. In this connection it has been found by Chandler and Heinicke (*11*) that fruiting reduced the growth of Olden-

berg apple trees. This effect is due in part to the fact that fewer and smaller leaves are produced on fruiting spurs than on nonfruiting spurs. The principal factor responsible for reduced vegetation, however, would seem to be the withdrawal of food materials from the tree into the fruit. Unless thinning were sufficiently severe to reduce materially the total crop, there would be little benefit to the tree, as the remaining fruit might still use most of the available elaborated materials.

Auchter (*5*), working with young nonbearing peach and apple trees from one side of which the leaves had been stripped, concluded that the foods manufactured on one side of the tree were used or stored mainly in that side or in the roots directly beneath. The results presented herewith seem to indicate that under certain conditions there may be a cross transfer of elaborated food materials. Thus, if one branch were bearing a very heavy crop and an adjacent branch a very light crop, there would be, to some extent at least, a tendency toward equalization of the food materials.

From defoliation experiments Magness (*27*), Roberts (*40*), and Harvey and Murneek (*23*) have shown that there is considerable individuality in buds and spurs and that they depend largely if not entirely upon their own leaves for development and blossom-bud formation. On the other hand, Hooker and Bradford (*25*) found with bearing trees that under some conditions there seemed to be no such localization of factors. Since apples require considerably more leaves than are normally present on one spur to supply sufficient material for normal development, and since they can apparently utilize material elaborated at some distance for additional foods, it would seem that the presence of fruit would have an effect on the food supply of spurs and buds for some distance from it.

It has been recognized that blossom thinning may influence fruit-bud formation, but there has been little previous evidence to show that thinning of the fruit later in the season would effect blossom-bud differentiation. Paddock and Charles (*38*) conclude from experiments in shading that fruit buds are differentiated previous to the time indicated by microscopic examination and that treatments following blossoming have no effect on differentiation except on secondary growth. The data presented in this bulletin conclusively show that treatments even as late as the middle of June, if sufficiently severe, may inhibit or greatly increase blossom-bud differentiation in the apple.

The results obtained have a direct bearing on the practice of thinning. They indicate that the leaves do not need to be directly adjacent to the fruit in order for it to obtain satisfactory size and quality. Thus, one branch might be allowed to bear a somewhat heavier crop provided an adjacent branch had a very light crop or no crop. Furthermore, the fruit could be thinned from the outer ends of the branches and be left correspondingly thick farther back on the branches where the weight would be less likely to cause breakage. Such a practice, however, would probably result in less color on red varieties, owing to less exposure to light. Similarly, from the standpoint of size and quality two apples might be allowed to grow on one spur provided there was sufficient leaf area on other parts of the branch to develop them properly.

In publications dealing with thinning it is usually recommended that fruit be thinned to a certain number of inches between fruits. In

view of the results given here it would seem more desirable to base thinning operations on the number and size of leaves per fruit. By this it is not meant that the leaves should be counted or measured, but that the size of the leaves and their thickness on the branches or trees should be considered. Thus, when a tree is bearing heavily and the leaves are small and scattered, the fruits should be thinned to a much greater distance apart than on a tree where the leaves are large, vigorous, and close together.

It has long been recognized that thinning apples and thus increasing the leaf area per fruit increased the size of the apples. The importance of thinning on dessert quality and color has not been so well recognized. Fruit grown with a small number of leaves in these tests was of very poor quality. Of the varieties studied this was particularly true of Delicious and least so of Jonathan.

In most thinning experiments the objective has been to increase the size of the fruit without materially decreasing the total yield of the tree. It is improbable that any benefit can be obtained by the tree from thinning that does not materially reduce the total crop of fruit. In most cases, however, thinning experiments have resulted in more or less reduction in total crop. The maximum distance between fruits has usually been not more than 10 to 12 inches. This probably would not give as many leaves per apple as seem to be necessary for the formation of blossom buds as well as the growth of the fruit of varieties markedly biennial in habit.

It is not claimed from the evidence presented that a biennially bearing tree can be brought into annual bearing by thinning. The evidence strongly indicates, however, that thinning of the fruit may be an important factor in maintaining trees in regular annual bearing. It also indicates that severe thinning to reduce the fruit crop, as well as pruning and fertilizing to stimulate growth and leaf area, should be resorted to in any effort to change biennial trees into annual bearers.

SUMMARY

Apples were grown on both ringed and unringed branches with different leaf areas per apple and with a given leaf area at different distances and different directions from the fruit. Growth measurements were made of the fruit during the growing season, and the chemical composition was determined following harvest. Bud differentiation was determined on the branches with the different leaf areas per apple.

On unringed branches the variation in leaf area had no appreciable effect on the composition of the fruit and very little effect on the size.

On ringed branches there was an increase in size of fruit with an increase in leaf area. With the varieties studied nearly maximum growth was usually obtained with about 30 leaves per apple, and increase in leaf area above this point had relatively little effect on the size of the fruit. Increase in size even with small leaf areas was not directly proportional to the increase in leaf area per apple. With a given leaf area the size of the fruit at the end of the season was correlated with the size of the fruit early in the season.

The percentage of dry weight and total sugars increased with increased leaf area on ringed branches. The increases in total sugars were due primarily to increases in nonreducing sugars.

Good dessert quality was associated with the high concentration of total sugars found in fruit grown with a large leaf area. About 30

leaves per apple were necessary to produce good quality for the variety. The ground color of fruit grown with a small number of leaves was greener and the fruit was lacking in red color as compared with fruit grown with leaves sufficient to produce good size and quality.

In the case of the Ben Davis variety the firmness of the fruit after storage decreased with an increase in the leaf area per apple. In the case of the York Imperial, Baldwin, and Jonathan varieties there was a decrease in firmness of the fruit with an increase in leaf area to about 20 leaves per apple. Above 20 leaves per apple there was an increase in firmness with a further increase in leaf area.

Although the fruit requires a rather large leaf area for full development, the leaves may be a considerable distance from the fruit. Practically no reduction in the size and composition of the fruit occurred when no leaves were less than 135 cm (4½ feet) from Grimes Golden, 180 cm (6 feet) from Ben Davis and York Imperial, 200 cm (6½ feet) from Jonathan, and over 300 cm (10 feet) from Baldwin, as compared with fruit grown with the same number of leaves that were immediately adjacent to the fruit.

Apples may obtain elaborated foods with equal facility from leaves that are above the fruit, from leaves that are below the fruit, or from leaves that are on separate branches.

On ringed branches a small leaf area per apple inhibited blossom-bud formation, whereas a large leaf area caused most of the spurs to form blossom buds. About 20 to 30 leaves per fruit, depending on the variety and time of thinning, were necessary to produce sufficient blossom buds for a normal crop. Blossom-bud formation was associated with a relatively high sugar content in adjacent apples. Bud differentiation was greatly influenced by thinning treatments applied as late as June 25.

LITERATURE CITED

(1) Aldrich, W. W.
1932. effect of fruit thinning upon carbohydrate accumulation, formation of fruit buds, and set of bloom in apple trees. Amer. Soc. Hort. Sci. Proc. (1931) 28:599–604.

(2) Asami, Y., and Chang Chih Hu.
1928. studies on the correlation between the size of the fruit and some characters in the japanese pear. Nôgaku Kwaihô (Jour. Sci. Agr. Soc. [Japan]) 303:55–66, illus. [English abstract in Japan. Jour. Bot. 4:(31), 1928.]

(3) Auchter, E. C.
1917. five years' investigations in apple thinning. W. Va. Agr. Expt. Sta. Bul. 162, 56 p., illus.

(4) ———
[1920]. some influences of thinning, pollination, and fruit spur growth on the yearly performance record of fruit spurs and on the size of fruit produced. Amer. Soc. Hort. Sci. Proc. (1919) 16:118–131.

(5) ———
1923. is there normally a cross transfer of foods, water, and mineral nutrients in woody plants? Md. Agr. Expt. Sta. Bul. 257, 60 p.

(6) ——— and Schrader, A. L.
[1924]. fruit spur growth and fruit bud production in the apple. Amer. Soc. Hort. Sci. Proc. (1923) 20:127–144.

(7) ——— Schrader, A. L., Lagasse, F. S., and Aldrich, W. W.
[1927]. the effect of shade on the growth, fruit bud formation, and chemical composition of apple trees. Amer. Soc. Hort. Sci. Proc. (1926) 23:368–382.

(8) BAILEY, J. S.
1929. THE EFFECT OF APPLE BLOSSOM REMOVAL ON FLOWER BUD FORMATION. Amer. Soc. Hort. Sci. Proc. (1928) 25:198–201.
(9) BEACH, S. A.
1903. THINNING APPLES. N. Y. State Agr. Expt. Sta. Bul. 239, p. [197]–224, illus.
(10) BIDWELL, G. L., and STERLING, W. F.
1925. PRELIMINARY NOTES ON THE DIRECT DETERMINATION OF MOISTURE. Indus. and Engin. Chem. 17:147–149, illus.
(11) CHANDLER, W. H., and HEINICKE, A. J.
[1927]. THE EFFECT OF FRUITING ON THE GROWTH OF OLDENBURG TREES. Amer. Soc. Hort. Sci. Proc. (1926) 23:36–46.
(12) COIT, J. E.
1918. EFFECT OF ADJACENT LEAF AREA ON THE SUGAR CONTENT OF ORANGES. Amer. Soc. Hort. Sci. Proc. (1917) 14:92–93.
(13) CROW, J. W.
[1921]. BIENNIAL FRUIT BEARING IN THE APPLE. Amer. Soc. Hort. Sci. Proc. (1920) 17:52–54.
(14) CURTIS, O. F.
1920. THE UPWARD TRANSLOCATION OF FOODS IN WOODY PLANTS. I. TISSUES CONCERNED IN TRANSLOCATION. Amer. Jour. Bot. 7:101–124, illus.
(15) ———
1923. THE EFFECT OF RINGING A STEM ON THE UPWARD TRANSFER OF NITROGEN AND ASH CONSTITUENTS. Amer. Jour. Bot. 10:361–382, illus.
(16) ———
1925. STUDIES ON THE TISSUES CONCERNED IN THE TRANSFER OF SOLUTES IN PLANTS. THE EFFECT ON THE UPWARD TRANSFER OF SOLUTES OF CUTTING THE XYLEM AS COMPARED WITH THAT OF CUTTING THE PHLOEM. Ann. Bot. [London] 39: [573]–585.
(17) DRAIN, B. D.
[1925]. ANNUAL CROPS FROM BIENNIAL BEARING APPLE TREES. Amer. Soc. Hort. Sci. Proc. (1924) 21: 300–302.
(18) FLETCHER, L. A.
1930. A PRELIMINARY STUDY OF THE FACTORS AFFECTING THE RED COLOR ON APPLES. Amer. Soc. Hort. Sci. Proc. (1929) 26:191–196.
(19) GARDNER, F. E.
1925. A STUDY OF THE CONDUCTIVE TISSUES IN SHOOTS OF THE BARTLETT PEAR AND THE RELATIONSHIP OF FOOD MOVEMENT TO DOMINANCE OF THE APICAL BUDS. Calif. Agr. Expt. Sta. Tech. Paper 20, 42 p., illus.
(20) GOURLEY, J. H., and NIGHTINGALE, G. T.
1921. THE EFFECT OF SHADING SOME HORTICULTURAL PLANTS. A PRELIMINARY REPORT. N. H. Agr. Expt. Sta. Tech. Bul. 18, 22 p., illus.
(21) HALLER, M. H., and MAGNESS, J. R.
[1926]. THE RELATION OF LEAF AREA TO THE GROWTH AND COMPOSITION OF APPLES. Amer. Soc. Hort. Sci. Proc. (1925) 22:189–196.
(22) HARLEY, C. P.
[1926]. NORMAL VARIATION IN THE CHEMICAL COMPOSITION OF FRUIT SPURS AND THE RELATION OF COMPOSITION TO FRUIT-BUD FORMATION. Amer. Soc. Hort. Sci. Proc. (1925) 22:134–146.
(23) HARVEY, E. M., and MURNEEK, A. E.
1921. THE RELATION OF CARBOHYDRATES AND NITROGEN TO THE BEHAVIOR OF APPLE SPURS. Oreg. Agr. Expt. Sta. Bul. 176, 47 p., illus.
(24) HOOKER, H. D., JR.
1920. SEASONAL CHANGES IN THE CHEMICAL COMPOSITION OF APPLE SPURS. Missouri Agr. Expt. Sta. Research Bul. 40, 51 p., illus.
(25) ——— and BRADFORD, F. C.
1921. LOCALIZATION OF THE FACTORS DETERMINING FRUIT BUD FORMATION. Missouri Agr. Expt. Sta. Research Bul. 47, 19 p.
(26) KRAUS, E. J., and KRAYBILL, H. R.
1918. VEGETATION AND REPRODUCTION WITH SPECIAL REFERENCE TO THE TOMATO. Oreg. Agr. Expt. Sta. Bul. 149:5–90.
(27) MAGNESS, J. R.
1917. STUDIES IN FRUIT-BUD FORMATION. Oreg. Agr. Expt. Sta. Bul. 146:3–27.

(28) MAGNESS, J. R.
1929. RELATION OF LEAF AREA TO SIZE AND QUALITY IN APPLES. Amer. Soc. Hort. Sci. Proc. (1928) 25:285–288.
(29) ———
1929. OBSERVATIONS ON COLOR DEVELOPMENT IN APPLES. Amer. Soc. Hort. Sci. Proc. (1928) 25:289–292.
(30) ——— DIEHL, H. C., HALLER, M. H., and GRAHAM, W. S., with the cooperation of CARRICK, D. B., HOWLETT, F. S., MARSHALL, R. E., PLAGGE, H. H., and RALEIGH, G. J.
1926. THE RIPENING, STORAGE, AND HANDLING OF APPLES. U. S. Dept. Agr. Bul. 1406, 64 p., illus.
(31) ——— and OVERLEY, F. L.
1930. RELATION OF LEAF AREA TO SIZE AND QUALITY OF APPLES AND PEARS. Amer. Soc. Hort. Sci. Proc. (1929) 26:160–162.
(32) MASON, T. G., and MASKELL, E. J.
1928. STUDIES ON THE TRANSPORT OF CARBOHYDRATES IN THE COTTON PLANT. I. A STUDY OF DIURNAL VARIATION IN THE CARBOHYDRATES OF LEAF, BARK, AND WOOD, AND OF THE EFFECTS OF RINGING. Ann. Bot. [London] 42:[189]–253, illus.
(33) ——— and MASKELL, E. J.
1928. STUDIES ON THE TRANSPORT OF CARBOHYDRATES IN THE COTTON PLANT. II. THE FACTORS DETERMINING THE RATE AND THE DIRECTION OF MOVEMENT OF SUGARS. Ann. Bot. [London] 42:[571]–636, illus.
(34) MORRIS, O. M.
1921. STUDIES IN APPLE POLLINATION. Wash. Agr. Expt. Sta. Bul. 163, 32 p., illus.
(35) MURNEEK, A. E.
1926. EFFECTS OF CORRELATION BETWEEN VEGETATIVE AND REPRODUCTIVE FUNCTIONS IN THE TOMATO (LYCOPERSICON ESCULENTUM MILL.) Plant Physiol. 1:3–56, illus.
(36) ———
[1926]. IS FRUITING OF THE APPLE AN EXHAUSTIVE PROCESS? Amer. Soc. Hort. Sci. Proc. (1925) 22:196–200.
(37) ———
1928. NITROGEN AND CARBOHYDRATE DISTRIBUTION IN ORGANS OF THE BEARING APPLE SPUR. Missouri Agr. Expt. Sta. Research Bul. 119, 50 p., illus.
(38) PADDOCK, W., and CHARLES, F. G.
1929. THE EFFECT OF SHADE UPON FRUIT-BUD DIFFERENTIATION. Amer. Soc. Hort. Sci. Proc. (1928) 25:195–197.
(39) RASMUSSEN, E. J.
1930. THE PERIOD OF BLOSSOM-BUD DIFFERENTIATION IN THE BALDWIN AND MCINTOSH APPLES. Amer. Soc. Hort. Sci. Proc. (1929) 26:255–260, illus.
(40) ROBERTS, R. H.
1923. EFFECT OF DEFOLIATION UPON BLOSSOM BUD FORMATION: AMERICAN PLUM SPECIES. Wis. Agr. Expt. Sta. Research Bul. 56, 15 p., illus.
(41) THOMPSON, R. C.
1916. THE RELATION OF FRUIT GROWING TO SOIL FERTILITY. Ark. Agr. Expt. Sta. Bul. 123, 20 p.
(42) WHITEHOUSE, W. E.
1916. A STUDY OF VARIATION IN APPLES DURING THE GROWING SEASON. Oreg. Agr. Expt. Sta. Bul. 134, 13 p.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Horticultural Crops and Diseases	E. C. AUCHTER, *Principal Horticulturist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1933

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 337 DECEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

THE PORTABLE BAND SAWMILL AND SELECTIVE LOGGING IN THE LOBLOLLY PINE FORESTS OF NORTH CAROLINA

By R. D. GARVER,[1] *Senior Forester*, and J. B. CUNO, *Associate Wood Technologist, Forest Products Laboratory,*[2] *Branch of Research, Forest Service*

CONTENTS

	Page		Page
Introduction	1	Lumber prices	14
Purpose	2	Grades and value of lumber	14
Area studied	2	Production costs and lumber values compared	17
The portable band sawmill	6	Returns from different diameter cutting limits	21
Logging and milling methods	7	Application of results to utilization and forest practice in North Carolina	23
How the study was made	8	Log grades	26
Cost of producing lumber from logs and trees of different sizes	8	Volume and value of individual loblolly pine trees	28
Logging costs for loblolly pine trees	9	Conclusions	28
Overrun for loblolly pine and hardwood logs and trees	10		
Total production cost for loblolly pine logs and trees of different diameters	11		

INTRODUCTION

Since the Civil War many thousand acres of farms in North Carolina and other States in the coastal plain have been abandoned for agricultural purposes. Loblolly pine has taken the lead in seeding these areas. It has succeeded admirably because abundant viable seed is produced nearly every year and the species adapts itself readily to a variety of soil and moisture conditions. Such stands are normally even aged, or at least even aged in groups, and form a large part of the remaining pine timber of the region. The commercial range of loblolly pine in North Carolina alone is estimated to cover more than 22,000 square miles, practically all of which is second growth, either of forest or old-field origin. The few remaining virgin stands are being cut out from year to year, making the profitable operation of large lumber mills increasingly difficult.

This situation will inevitably result in the greater use of small mills even where a company has large holdings and desires to grow successive crops of timber on its lands. Profitable operation on a

[1] Acknowledgment is made of assistance received in this study from the Appalachian Forest Experiment Station; the Division of Forest Pathology, Bureau of Plant Industry; the North Carolina State Forest Service; the North Carolina Pine Association through its secretary, G. L. Hume; and an advisory committee consisting of P. R. Camp, J. W. Foreman, and G. J. Cherry. Especial acknowledgment is made to A. L. MacKinney, Appalachian Forest Experiment Station, for assistance in the field work and for the photographs, and to B. H. Paul and A. C. Wollin, Forest Products Laboratory, and L. N. Carter, North Carolina Forest Service, for assistance in the field work.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

145579°—32——1

long-time basis in these stands depends very largely on the adoption of a proper cutting system and the development of manufacturing practices that will produce lumber cheaply and efficiently enough to compete with the water-borne shipments from other regions that regularly come into the Atlantic seaboard markets.

PURPOSE

This bulletin gives information by diameter classes on the relative production cost and lumber grades and yields obtained when an old-field second-growth loblolly pine forest was cut by a new type of portable band sawmill. The information may be used in setting up logging practices that will exclude from the cut the trees that are too small to yield a satisfactory margin for profit and those that will pay larger returns if left for future growth. The new method of lumber

FIGURE 1.—The tract before logging

production described appears worthy of the consideration of all lumbermen interested in operating permanently on the coastal plain.

Selective cutting or logging as here used means a partial-cutting practice in which the large trees and the small defective ones are removed while the small and medium-sized thrifty ones are reserved for future growth and seed production.

AREA STUDIED

The area selected for study was representative of the old-field loblolly type of the Atlantic coastal plain (fig. 1) and was located in northeastern North Carolina. The furrows and ridges still in evidence showed that the land had been in some row crop, such as cotton or corn, before it was taken over by the stand of timber which now occupies it. The stand averaged 55 years in age but varied from 53 years to a very few individual trees that were about 70 years old.

For all practical purposes, however, the stand may be considered even aged.

Loblolly pine made up 94.1 per cent of the volume of the stand considering only trees 8 inches in diameter and larger, even though there were 17 other species, mostly gum, maple, and oaks, associated with it. On a number basis 92 per cent of the dominant trees were loblolly pine. Taking into account all trees 8 inches in diameter and larger, the study area of 8 acres averaged 20,770 board feet, lumber tally, of pine and 1,306 board feet of hardwoods per acre. The largest loblolly pine on the tract was 22 inches in diameter and the largest hardwood 19 inches in diameter.

On an average the area was 80 per cent stocked (trees 4 inches in diameter and larger), as gaged by the ratio of its basal area to yield-table values, and had a site index [3] of about 85 feet.

Table 1, which is based on the data from 8 acres, as are all the other tables, gives the composition of the stand and shows that there were 337 trees per acre, 188 of which were loblolly pine, 5 shortleaf pine, varying from 3 to 22 inches in diameter, and 149 hardwoods, about three-fourths of which were from 3 to 6 inches in diameter. The stand, therefore, was made up of an overstory of pine with an understory of small hardwoods.

TABLE 1.—*Average number of trees per acre by species—old-field loblolly pine, Middle Atlantic coastal plain*

Species	Average number of trees per acre of a diameter breast high of—			
	3 to 6 inches	7 to 12 inches	13 inches and up	Total
Loblolly pine (*Pinus taeda*)	9.2	119.4	59.1	187.7
Red gum (*Liquidambar styraciflua*)	34.0	27.8	2.9	64.7
Black gum (*Nyssa sylvatica*)	42.4	2.7		45.1
Red maple (*Acer rubrum*)	17.7	.9		18.6
White oak (*Quercus alba*)	4.0	.7		4.7
Shortleaf pine (*Pinus echinata*)	2.6	2.0	.1	4.7
Post oak (*Quercus stellata*)	3.9	.5		4.4
Holly (*Ilex opaca*)	1.7			1.7
Sourwood (*Oxydendrum arboreum*)	1.2			1.2
Southern red oak (*Quercus rubra*)	1.1			1.1
Swamp red oak (*Quercus rubra pagodaefolia*)	.8	.2		1.0
Willow oak (*Quercus phellos*)	.4	.1	.4	.9
Hickory (*Hicoria* sp.)	.4			.4
Dogwood (*Cornus florida*)	.4			.4
Haw (*Crataegus* sp.)	.2			.2
Winged elm (*Ulmus alata*)	.1			.1
Yellow poplar (*Liriodendron tulipifera*)	.1			.1
Persimmon (*Diospyros virginiana*)	.1			.1
Total	120.3	154.3	62.5	337.1

For the purpose of studying the effect of different degrees of cutting on the growth of the residual stand, the establishment and growth of reproduction, and to illustrate the practicability of logging successfully in partly cut stands, four sample plots of 2 acres each, all lying close to each other, were established.[4] In selectively cutting these plots the aim was to remove sufficient volume to make logging practicable and at the same time favor loblolly pine and reserve enough

[3] Site index is based on the average height of the dominant trees in the stand at the age of 50 years.

[4] These plots were established by A. L. MacKinney and C. F. Korstian, Appalachian Forest Experiment Station.

thrifty, small, and medium-sized trees to dominate the type, seed the land, and provide a future cut. (Fig. 2.) The amount of timber removed varied from 9,818 to 16,562 board feet per acre. The proportion of the stand removed varied from 53 to 82 per cent and averaged 71 per cent. Under the selective logging plan the mature and poorly formed loblolly pine and all the merchantable hardwoods were removed. This practice resulted in cutting an average of 85.5 loblolly pine trees and 37.8 hardwood trees per acre. There remained

FIGURE 2.—The tract after selective cutting

an average of 102.2 pine trees per acre, varying from 3 to 17 inches in diameter, and 111.6 hardwood trees, varying from 3 to 10 inches in diameter. The volume of the pine left standing, considering only trees 8 inches in diameter and larger, was 6,508 board feet, lumber tally, per acre. The board-foot volume of hardwoods left was negligible.

Table 2 describes the study area further by showing the stand both by the number of trees before and after cutting and the volume distribution by diameter class before cutting.

TABLE 2.—*Composition of old-field loblolly pine trees cut and left per acre in the Middle Atlantic coastal plain*

Diameter breast high in inches	Loblolly pine			Hardwoods			Volume of trees 8 inches and over in board feet lumber tally		
	Cut	Left	Total	Cut	Left	Total	Loblolly pine	Hardwoods	Total
	Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Per cent*	*Per cent*	*Per cent*
3	----	0.9	0.9	12.6	34.6	47.2	----	----	----
4	0.2	.9	1.1	5.8	24.1	29.9	----	----	----
5	.5	.9	1.4	1.9	18.0	19.9	----	----	----
6	1.0	4.8	5.8	1.1	13.0	14.1	----	----	----
7	3.0	11.1	14.1	.3	8.9	9.2	----	----	----
8	4.0	14.4	18.4	.5	7.5	8.0	3.0	19.6	4.4
9	4.5	19.2	23.7	2.4	4.5	6.9	4.0	13.3	4.7
10	6.0	17.7	23.7	4.1	1.0	5.1	7.1	13.6	7.6
11	8.4	13.6	22.0	3.1	----	3.1	9.7	12.1	9.9
12	10.0	7.5	17.5	2.6	----	2.6	10.1	13.7	10.4
13	10.7	5.2	15.9	1.9	----	1.9	11.9	12.4	12.0
14	9.2	3.5	12.7	.8	----	.8	11.4	5.9	11.0
15	9.6	1.4	11.0	----	----	----	12.2	----	11.2
16	6.6	.8	7.4	.4	----	.4	9.8	3.8	9.3
17	4.9	.3	5.2	.1	----	.1	8.2	1.8	7.7
18	3.2	----	3.2	.1	----	.1	5.7	1.7	5.3
19	2.2	----	2.2	.1	----	.1	4.1	2.1	3.9
20	.9	----	.9	----	----	----	1.6	----	1.5
21	.5	----	.5	----	----	----	1.0	----	.9
22	.1	----	.1	----	----	----	.2	----	.2
Total	85.5	102.2	187.7	37.8	111.6	149.4	100.0	100.0	100.0

Table 3 gives the volume distribution of the cut, taking all plots together, and has been used to compute the weighted-average costs and values given later in this bulletin.

TABLE 3.—*Volume distribution of loblolly pine and hardwoods as cut by diameters on a gross-log scale and dry-lumber tally, basis, and percentages of loblolly pine and hardwoods within diameter classes in the Middle Atlantic coastal plain*

Diameter breast high in inches	Loblolly pine		Hardwoods		Total		Within diameter classes			
							Gross log scale		Lumber tally	
	Gross log scale	Lumber tally	Gross log scale	Lumber tally	Gross log scale	Lumber tally	Loblolly pine	Hardwoods	Loblolly pine	Hardwoods
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
8	0.2	0.3	0.6	0.9	0.2	0.3	83.0	17.0	79.5	20.5
9	.4	.4	3.8	5.2	.6	.8	60.6	39.4	47.3	52.7
10	1.8	2.6	12.2	15.4	2.5	3.6	68.3	31.7	66.3	33.7
11	3.2	4.2	16.1	18.2	4.0	5.3	74.4	25.6	72.9	27.1
12	6.5	8.1	19.4	19.8	7.3	9.0	83.0	17.0	82.7	17.3
13	10.0	11.6	19.0	17.6	10.6	12.1	88.5	11.5	88.5	11.5
14	12.6	13.5	9.1	8.0	12.4	13.1	95.2	4.8	95.2	4.8
15	15.7	15.7	----	----	14.7	14.4	100.0	----	100.0	----
16	14.8	13.8	6.2	4.9	14.2	13.1	97.2	2.8	97.0	3.0
17	12.3	11.0	4.2	3.2	11.8	10.4	97.7	2.3	97.6	2.4
18	10.2	8.8	4.1	3.0	9.8	8.3	97.3	2.7	97.2	2.8
19	6.7	5.5	5.3	3.8	6.6	5.4	94.9	5.1	94.4	5.6
20	3.2	2.6	----	----	3.0	2.4	100.0	----	100.0	----
21	1.8	1.4	----	----	1.7	1.3	100.0	----	100.0	----
22	.6	.5	----	----	.6	.5	100.0	----	100.0	----

THE PORTABLE BAND SAWMILL

The portable band sawmill used in this study has the power unit, rolls, carriage, deck, sawdust carrier, and log conveyor mounted on a specially constructed flat car. (Figs. 3 and 4.) The mill has 54-inch wheels and uses an 18-gage saw that is swaged to cut about a $\frac{3}{32}$-inch kerf. The carriage is mounted permanently in alignment with the saw, has five knees with patent screw dogs and hand-operated setworks. The power unit consists of a 50-horsepower gasoline engine connected to the saw with a line shaft and a clutch. The logs are hoisted from the ground to the deck on the car by means of a chain conveyor. The sawdust is removed by means of a chain equipped with lugs and running in a trough.

FIGURE 3.—Portable band sawmill mounted on a special steel-frame flat car for easy transportation from setting to setting

Because the mill is mounted on a flat car, it was necessary to build a light standard-gage railway track on which to move the mill about the woods. Gasoline engines were used in place of steam locomotives, and small cars in place of standard freight cars.

Under favorable conditions this mill can be pulled up, moved one-half mile, and made ready for operation in one to two hours. When the mill is moved the log hoist and the sawdust carrier are folded on the deck of the car. Before the mill is placed in operation the car is leveled and blocked on the four corners in order to obtain rigidity and steadiness. The log hoist is then dropped to the ground and the sawdust conveyor put in place. The mill is then ready to run.

Five men are required to operate the mill and one man to pile the lumber on a car ready for transportation to a concentration yard. In addition, a sixth man spent one-third of his time in filing the saws. The output of the mill averaged about 9,000 board feet, lumber tally, per 10-hour day when cutting second-growth loblolly pine.

LOGGING AND MILLING METHODS

Spurs were built into the woods, old grades from the previous logging being used wherever possible. In general, it was planned to keep log cutting and milling balanced and shorten the log haul as much as possible by moving the mill often. The woods crew consisted of 3 log cutters, 1 log buncher, 1 swamper and cart loader, and 2 haulers. On short hauls one wagon was sufficient to keep the mill busy; three wagons kept two mills in logs most of the time. The logs were unloaded at the foot of the log hoist at the mill. The ground man rolled them to the incline chains which raised them to the deck on the flat car. Here they were scaled and placed in position by the man who assisted the sawyer in turning and placing them on the carriage. The sawyer did the sawing and handled the setworks.

FIGURE 4.—Typical set-up for a portable band mill. The lumber is loaded directly on a flat car for hauling to a concentration yard. Sawdust and unused slabs are left in the woods

Care was used in sawing the logs so as to get the best yield in both quantity and quality. The logs were turned on the carriage whenever it was of advantage to do so. The logs were slabbed thinly. The lumber was of even thickness, and there was no saw snaking, because an automatic speed control on the carriage prevented the log from being fed into the saw too fast.

Since no edging was done in the woods, a part of the lumber was bark edged and a part square edged.

The lumber was passed on by the tail sawyer to the lumber loader, who bulk piled it on a car ready for hauling to the concentration yard. At the yard it was kiln-dried, put through an edger and trimmer, and made ready for shipment or for storage in the dry shed. The slabs were thrown to the ground to be picked up later as needed for fuel for the boiler at the concentration yard.

HOW THE STUDY WAS MADE

In obtaining the information presented here, a crew of men studied the timber cut from each plot as it passed through the different logging and milling operations and recorded, by individual logs, the volume, the time required for each step of lumber production, and the grades and amounts of lumber produced from each log and tree. Each log was numbered in the woods so that it could be identified with the tree from which it came at any time during the different steps of lumber production. Because the same logs were studied in the woods and at the mill, it was possible to obtain production costs and lumber values for the trees by adding up the corresponding figures for the logs that made up each tree. The cost figures and wage scales prevailing at the operation where the study was made were combined with the time studies to give a basis for computing the costs by tree and log diameter classes. For logs 8 inches in diameter and larger the Doyle log scale was used for determining the volume in board feet. For logs under 8 inches in diameter the Doyle rule was adjusted to give a scale more nearly in accord with actual volume of the log. Instead of subtracting 4 inches for slabs, as is done with the standard Doyle rule, only 3⅝ inches were subtracted for 7-inch logs, 3½ inches for 6-inch logs, and 2⅝ inches for 5-inch logs. This modified rule gives 5 board feet for 5-inch logs, 7 board feet for 6-inch logs, and 11 board feet for 7-inch logs, all 16 feet long—as compared to values of 1, 4, and 9 board feet, respectively, by the standard Doyle rule. It is well known that for small logs the Doyle rule gives a ridiculously low scale, and there are a number of ways in which lumbermen correct this; the most common is to give the logs below 8 inches in diameter a scale equal to their length in feet. This practice causes a large underrun in logs of approximately 5 inches in diameter that is inconsistent with the rest of the rule. The adjusted log-scale figures used in this bulletin for small logs give an overrun that corresponds generally with the trend in logs of more than 7 inches diameter.

The log-run costs which follow are based on the volume distribution of the cut among the different sized trees as found in this study.

COST OF PRODUCING LUMBER FROM LOGS AND TREES OF DIFFERENT SIZES

Trees that are too small to pay their way are often taken to the mill. The loss they cause is not apparent, because lumbermen compute their costs and lumber values on the basis of log run. For efficient and most profitable operation, information should be available on costs and lumber values by tree-diameter classes. The next several tables present this information and bring out the economic aspects of selective logging and some of the advantages of sustained-yield operations. In cost accounting it is necessary to remember that certain items, such as felling and hauling, vary with the size of the timber cut, while others, such as taxes on the lumber, vary with the price it brings. Another class of costs, such as permanent improvements, is considered constant per acre and varies only with the relative amount of timber removed from each acre in comparison with the total stand.

Barge expense is the only cost item in the costs that is unusual. In this operation the barge was substituted for the railroad to good

advantage in hauling lumber from the woods to a central shipping point where it could be distributed either by rail or by boat.

The cost classification is explained by footnotes to each table. Interest on invested capital, Federal income tax, and stumpage have not been included in these costs.

LOGGING COSTS FOR LOBLOLLY PINE TREES

The logging costs at this operation are different from those at most places because they end when the logs are dropped at the spur where the mill is located and do not include log transportation, unloading, or pond charges. Table 4 gives the average woods-production costs and the logging cost for each size of tree on a gross log-scale basis. It is five times more costly per thousand board feet gross log scale to log 9-inch trees than 21-inch trees. This ratio was obtained from the actual time consumed in doing the work. Time records obtained with stop watches were combined with the company's wage scales and costs in order to compute the production cost for trees of different diameters. The ratio of costs among diameter classes is somewhat higher than would prevail if another scale rule, such as the Scribner, were used (p. 8).

TABLE 4.—*Total logging costs per thousand board feet gross log scale (Doyle) by diameter classes for loblolly pine trees*

Logging cost items	Classification of costs [1]	Weighted average production cost per thousand board feet gross log scale	Total logging costs, by d. b. h. classes							
			8 inches	9 inches	10 inches	11 inches	12 inches	13 inches	14 inches	15 inches
		Dollars	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
Sawing (felling and bucking)	VT	1.38	6.40	5.12	3.63	2.65	2.15	1.77	1.48	1.26
Bunching and wagon haul (animal feed included)	VMT	2.41	7.91	6.49	5.33	4.37	3.59	3.02	2.60	2.31
Supplies (camp and logging)	VMT	.11	.35	.31	.25	.21	.16	.15	.12	.11
Depreciation of equipment (logging)	VMT	.20	.68	.55	.45	.38	.31	.25	.22	.19
General expense (logging)	V Tot.	1.17	4.34	3.53	2.74	2.15	1.76	1.47	1.26	1.10
Total		5.27	19.68	16.00	12.40	9.76	7.97	6.66	5.68	4.17
Overrun—per cent		57.2	151	137	123	109	95	82	68	57
Total logging costs converted to a lumber-tally basis—dollars		3.35	7.84	6.75	5.56	4.67	4.09	3.66	3.38	3.17

Logging cost items	Classification of costs [1]	Weighted average production cost per thousand board feet gross log scale	Total logging costs, by d. b. h. classes						
			16 inches	17 inches	18 inches	19 inches	20 inches	21 inches	22 inches
		Dollars	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
Sawing (felling and bucking)	VT	1.38	1.12	1.04	0.96	0.91	0.88	0.86	0.84
Bunching and wagon haul (animal feed included)	VMT	2.41	2.06	1.89	1.73	1.62	1.52	1.45	1.35
Supplies (camp and logging)	VMT	.11	.09	.08	.08	.08	.06	.06	.06
Depreciation of equipment (logging)	VMT	.20	.18	.15	.15	.14	.13	.12	.11
General expense (logging)	V Tot.	1.17	.97	.90	.83	.78	.74	.71	.67
Total		5.27	4.42	4.06	3.75	3.53	3.33	3.20	3.03
Overrun—per cent		57.2	47	40	34	30	27	25	22
Total logging costs converted to a lumber-tally basis—dollars		3.35	3.01	2.90	2.80	2.72	2.62	2.56	2.48

[1] Classification of costs: VT, varies with time per thousand board feet; VMT, varies with milling time per thousand board feet; V Tot., varies with total of logging costs.

Similar trends in cost apply to logs as well as to trees. Logging costs for logs on a gross log-scale basis are therefore not shown but may be readily computed from the overrun table and lumber tally costs if desired.

Separate costs for hardwoods are not shown, since an examination of the field data shows that for hardwood trees of the same diameter the costs would be practically the same as those for pine.

OVERRUN FOR LOBLOLLY PINE AND HARDWOOD LOGS AND TREES

Since log scale is used as a basis for payment for woods work and for the purchase of logs, it is important to know something about the overrun for logs and trees of different sizes. Gross overrun is the amount by which the lumber tally exceeds the gross log scale. Net overrun is the amount by which the lumber tally exceeds the net log scale (gross scale less deductions for defects). Table 5 gives figures for overrun and percentage of defect for loblolly pine and hardwood logs and trees. The average overrun for the pine was 57.2 per cent, which means that for each 1,000 feet, gross scale, of logs, 1,572 feet of lumber were obtained. This is a high yield as compared with that from a large band sawmill cutting similar timber where about 10 per cent less lumber was obtained. The high yield results principally from the thin saw used in cutting the logs into lumber and the practice of edging the lumber after it has been dried. Overrun percentages are applied in converting log-scale costs to a lumber-tally basis as follows: Table 4 gives average logging costs as $5.27 per thousand board feet log scale, which reduced to a lumber-tally basis $\left(\frac{\$5.27}{157.2}\times 100\right)$ becomes $3.35 per thousand board feet, lumber tally. Similar computations have been made for all items of logging, and the results hereafter are shown on a lumber-tally basis. Overrun in the hardwood was particularly high because the lumber was not edged closely and on an average the trees were small.

TABLE 5.—*Gross and net overrun*[1] *and percentage defect for loblolly pine and hardwood logs and trees*

LOBLOLLY PINE

Logs				Trees			
Top diameter inside bark in inches	Overrun		Defect	Diameter breast high	Overrun		Defect
	Gross	Net			Gross	Net	
	Per cent	*Per cent*	*Per cent*	*Inches*	*Per cent*	*Per cent*	*Per cent*
5	211	228	5.2	8	151	183	11.3
6	182	200	6.0	9	137	165	10.6
7	153	170	6.3	10	123	146	9.4
8	125	141	6.6	11	109	129	8.7
9	96	112	7.5	12	95	112	8.0
10	67	82	8.2	13	82	95	6.7
11	47	59	7.5	14	68	81	7.2
12	35	43	5.5	15	57	67	6.0
13	27	32	3.8	16	47	55	5.2
14	20	25	4.0	17	40	46	4.1
15	14	18	3.4	18	34	40	4.3
16	8	12	3.6	19	30	35	3.7
17	3	7	3.7	20	27	32	3.8
				21	25	29	3.1
				22	22	26	3.2
Weighted average	57.2	67.2	6.0		57.2	67.2	6.0

[1] Based on modified Doyle rule and dry lumber tally (p. 8).

TABLE 5.—*Gross and net overrun and percentage defect for loblolly pine and hardwood logs and trees*—Continued

HARDWOODS

Logs				Trees			
Top diameter inside bark in inches	Overrun		Defect	Diameter breast high	Overrun		Defect
	Gross	Net			Gross	Net	
	Per cent	*Per cent*	*Per cent*	*Inches*	*Per cent*	*Per cent*	*Per cent*
5	245	288	11.1	8	200	237	11.0
6	212	244	9.3	9	173	206	10.8
7	175	197	7.4	10	150	174	8.8
8	137	154	6.7	11	125	142	7.0
9	103	118	6.9	12	103	117	6.5
10	74	80	3.3	13	85	95	5.1
11	50	54	2.6	14	73	80	3.9
12	38	40	1.4	15	63	70	4.1
13	32	33	.8	16	55	62	4.3
14	26	28	1.6	17	50	56	3.8
				18	45	51	4.0
				19	41	46	3.4
Weighted average	98.5	112.1	6.4		98.5	112.1	6.4

The amount of defect in the pine and hardwoods was practically the same, being 6 and 6.4 per cent, respectively. Defect as used here includes the deductions made from the gross volume of the log to cover crook, rot, surface defect, fire injury, and operating damage.

TOTAL PRODUCTION COST FOR LOBLOLLY PINE LOGS AND TREES OF DIFFERENT DIAMETERS

Logging costs converted to a lumber-tally basis by means of overrun figures can be added directly to the milling costs. This has been done, and the lumber-production costs for trees and logs of different diameters are shown in Table 6. Taking all items together, it costs twice as much per thousand board feet to produce lumber from 9-inch trees as from 22-inch trees, which corresponds exactly with the ratio obtained for similar diameters in a large band sawmill. With the portable band sawmill the milling cost alone was 2.46 times as much per thousand board feet for 9-inch trees as for 22-inch trees, as compared with a ratio of 2 in the large band sawmill for trees of similar diameters. This results because the speed of the carriage in the small sawmill is necessarily held to a low maximum, while in the large sawmills such a provision is not necessary.

TABLE 6.—*Total production cost per thousand board feet, lumber tally, of dry lumber for loblolly pine trees and logs of different diameters*

TREES

Cost items	Classification of costs[1]	Weighted average production cost per thousand board feet lumber tally	Diameter breast high							
			8 inches	9 inches	10 inches	11 inches	12 inches	13 inches	14 inches	15 inches
		Dolls.	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
Sawing (felling and bucking)	VT	0.88	2.55	2.16	1.63	1.27	1.10	0.97	0.88	0.80
Bunching and wagon haul (animal feed included)	VMT	1.53	3.15	2.74	2.39	2.09	1.84	1.66	1.55	1.47
Supplies (camp and logging)	VMT	.07	.14	.13	.11	.10	.08	.08	.07	.07
Depreciation of equipment (logging)	VMT	.13	.27	.23	.20	.18	.16	.14	.13	.12
General expense: Foreman, crosscut filer, repairman and emergency sawyer, stableman, and miscellaneous	V Tot.	.74	1.73	1.49	1.23	1.03	.90	.81	.75	.70
Railroad construction	CA	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Sawmill labor, including band-saw filer	VT	1.94	4.00	3.48	3.03	2.65	2.33	2.10	1.96	1.86
Sawmill supplies, repairs, miscellaneous	VMT	.71	1.46	1.27	1.11	.97	.85	.77	.72	.68
Railroad operation, labor, gasoline, oil	VMT	.74	1.53	1.33	1.16	1.01	.89	.80	.75	.71
Kiln, labor and supplies	V No.	[2] 94	1.49	1.39	1.30	1.20	1.12	1.04	.98	.92
Rip mill, labor and supplies	V No.	[3] 1.07	1.70	1.61	1.49	1.39	1.29	1.20	1.12	1.05
Storage shed, labor	V No.	.46	.72	.68	.64	.59	.55	.51	.48	.45
Barge expense, labor and towage	V No.[4]	[5] 1.50	2.13	2.04	1.93	1.83	1.73	1.64	1.56	1.49
General expense: Foreman, watchman, miscellaneous	VMT	.72	1.48	1.29	1.12	.98	.86	.78	.73	.69
Insurance, workmen's compensation	VMT	.13	.27	.23	.20	.18	.16	.14	.13	.12
Taxes on finishing plant	VMT	.07	.14	.13	.11	.10	.08	.08	.07	.07
Taxes on lumber	VP	.10	.08	.09	.09	.09	.09	.10	.10	.10
Discount and allowance	VP	.25	.21	.22	.22	.23	.23	.24	.25	.25
Standing-timber expense	VMT	1.25	2.58	2.24	1.95	1.71	1.50	1.35	1.26	1.20
Depreciation, plant and equipment	VMT	.96	1.98	1.72	1.50	1.31	1.15	1.04	.97	.92
Selling expense	VP	1.25	1.06	1.08	1.10	1.13	1.16	1.20	1.23	1.26
Total		16.94	30.17	27.05	24.01	21.54	19.57	18.15	17.19	16.43

Cost items	Classification of costs[1]	Weighted average production cost per thousand board feet lumber tally	Diameter breast high						
			16 inches	17 inches	18 inches	19 inches	20 inches	21 inches	22 inches
		Dolls.	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
Sawing (felling and bucking)	VT	0.88	0.76	0.74	0.72	0.70	0.69	0.69	0.69
Bunching and wagon haul (animal feed included)	VMT	1.53	1.40	1.35	1.29	1.25	1.20	1.16	1.11
Supplies (camp and logging)	VMT	.07	.06	.06	.06	.06	.05	.05	.05
Depreciation of equipment (logging)	VMT	.13	.12	.11	.11	.11	.10	.10	.09
General expense: Foreman, crosscut filer, repairman and emergency sawyer, stableman, and miscellaneous	V Tot.	.74	.66	.64	.62	.60	.58	.57	.55
Railroad construction	CA	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Sawmill labor, including band-saw filer	VT	1.94	1.78	1.71	1.64	1.58	1.52	1.47	1.41
Sawmill supplies, repairs, miscellaneous	VMT	.71	.65	.63	.60	.58	.56	.54	.52
Railroad operation, labor, gasoline, oil	VMT	.74	.68	.65	.63	.60	.58	.56	.54
Kiln, labor and supplies	V No.	[2] 94	.87	.82	.78	.75	.73	.72	.70
Rip mill, labor and supplies	V No.	[3] 1.07	.99	.94	.90	.87	.85	.83	.81
Storage shed, labor	V No.	.46	.42	.40	.38	.36	.35	.34	.34
Barge expense, labor and towage	V No.[4]	[5] 1.50	1.43	1.38	1.34	1.31	1.29	1.27	1.25
General expense: Foreman, watchman, miscellaneous	VMT	.72	.66	.63	.61	.59	.56	.55	.52
Insurance, workmen's compensation	VMT	.13	.12	.11	.11	.11	.10	.10	.09
Taxes on finishing plant	VMT	.07	.06	.06	.06	.06	.05	.05	.05
Taxes on lumber	VP	.10	.10	.10	.10	.10	.10	.10	.10
Discount and allowance	VP	.25	.26	.26	.26	.26	.26	.26	.25
Standing-timber expense	VMT	1.25	1.15	1.10	1.06	1.02	.98	.95	.91
Depreciation, plant and equipment	VMT	.96	.88	.85	.81	.78	.75	.73	.70
Selling expense	VP	1.25	1.29	1.30	1.32	1.32	1.31	1.28	1.27
Total		16.94	15.84	15.34	14.90	14.51	14.11	13.82	13.45

[1] Classification of costs: VT, varies with time per thousand board feet; VMT, varies with milling time per thousand board feet; V Tot., varies with total of logging costs; CA, constant with area; V No., varies with the number of pieces per thousand board feet lumber tally; VP, varies with price of lumber.

[2] Labor $0.90. [3] Labor $1.02. [4] Towage was constant per thousand board feet lumber tally. [5] Labor $1.

TABLE 6.—*Total production cost per thousand board feet, lumber tally, of dry lumber for loblolly pine trees and logs of different diameters*—Continued

LOGS

Cost items	Classification of costs [1]	Weighted average production cost per thousand board feet lumber tally	Top diameter inside bark						
			5 inches	6 inches	7 inches	8 inches	9 inches	10 inches	11 inches
		Dolls.	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
Sawing (felling and bucking)	VT	0.88	1.59	1.38	1.20	1.05	0.96	0.94	0.92
Bunching and wagon haul (animal feed included)	VMT	1.53	2.94	2.44	2.07	1.82	1.66	1.54	1.45
Supplies (camp and logging)	VMT	.07	.13	.11	.09	.08	.08	.07	.07
Depreciation of equipment (logging)	VMT	.13	.25	.21	.18	.15	.14	.13	.12
General expense: Foreman, crosscut-saw filer, repairman and emergency sawyer, stableman, and miscellaneous	V Tot.	.74	1.39	1.17	1.00	.88	.81	.76	.73
Railroad construction	CA	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Sawmill labor, including band-saw filer	VT	1.94	3.73	3.10	2.62	2.31	2.10	1.95	1.84
Sawmill supplies, repairs, miscellaneous	VMT	.71	1.37	1.13	.96	.85	.77	.71	.67
Railroad operation, labor, gasoline, oil	VMT	.74	1.42	1.18	1.00	.88	.80	.74	.70
Kiln, labor and supplies	V No.	[2] .94	1.74	1.60	1.44	1.26	1.11	.99	.91
Rip mill, labor and supplies	V No.	[3] 1.07	1.98	1.82	1.64	1.43	1.26	1.12	1.04
Storage shed, labor	V No.	.46	.80	.73	.66	.58	.51	.45	.42
Barge expense, labor and towage	V No.	[4] [5] 1.50	2.31	2.20	2.04	1.85	1.69	1.55	1.48
General expense: Foreman, watchman, miscellaneous	VMT	.72	1.38	1.15	.97	.86	.78	.72	.68
Insurance, workmen's compensation	VMT	.13	.25	.21	.18	.15	.14	.13	.12
Taxes on finishing plant	VMT	.07	.13	.11	.09	.08	.08	.07	.07
Taxes on lumber	VP	.10	.10	.08	.09	.09	.09	.10	.10
Discount and allowance	VP	.25	.21	.21	.22	.22	.23	.24	.25
Standing timber expense	VMT	1.25	2.40	2.00	1.69	1.49	1.35	1.26	1.19
Depreciation, plant and equipment	VMT	.96	1.85	1.53	1.30	1.14	1.04	.96	.91
Selling expense	VP	1.25	1.06	1.07	1.09	1.12	1.15	1.19	1.24
Total		16.94	28.53	24.93	22.03	19.79	18.25	17.12	16.41

Cost items	Classification of costs [1]	Weighted average production cost per thousand board feet lumber tally	Top diameter inside bark					
			12 inches	13 inches	14 inches	15 inches	16 inches	17 inches
		Dolls.	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*
Sawing (felling and bucking)	VT	0.88	0.89	0.86	0.83	0.81	0.79	0.77
Bunching and wagon haul (animal feed included)	VMT	1.53	1.37	1.29	1.23	1.17	1.11	1.06
Supplies (camp and logging)	VMT	.07	.06	.06	.06	.05	.05	.05
Depreciation of equipment (logging)	VMT	.13	.12	.11	.10	.10	.09	.09
General expense: Foreman, crosscut-saw filer, repairman and emergency sawyer, stableman, and miscellaneous	V Tot.	.74	.69	.66	.63	.60	.58	.56
Railroad construction	CA	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Sawmill labor, including band-saw filer	VT	1.94	1.74	1.64	1.56	1.48	1.41	1.35
Sawmill supplies, repairs, miscellaneous	VMT	.71	.64	.60	.57	.54	.52	.49
Railroad operation, labor, gasoline, oil	VMT	.74	.66	.63	.60	.56	.54	.51
Kiln, labor and supplies	V No.	[2] .94	.85	.80	.77	.74	.72	.71
Rip mill, labor and supplies	V No.	[3] 1.07	.96	.91	.88	.85	.82	.81
Storage shed, labor	V No.	.46	.39	.37	.35	.34	.33	.33
Barge expense, labor and towage	V No.	[4] [5] 1.50	1.41	1.36	1.31	1.29	1.27	1.27
General expense: Foreman, watchman, miscellaneous	VMT	.72	.65	.61	.58	.55	.52	.50
Insurance, workmen's compensation	VMT	.13	.12	.11	.10	.10	.09	.09
Taxes on finishing plant	VMT	.07	.06	.06	.06	.05	.05	.05
Taxes on lumber	VP	.10	.10	.11	.12	.12	.12	.13
Discount and allowance	VP	.25	.26	.28	.29	.30	.31	.32
Standing timber expense	VMT	1.25	1.12	1.06	1.01	.95	.91	.87
Depreciation, plant and equipment	VMT	.96	.86	.81	.77	.73	.70	.67
Selling expense	VP	1.25	1.31	1.38	1.44	1.50	1.55	1.58
Total		16.94	15.76	15.21	14.76	14.33	13.98	13.71

[1] Classification of costs: VT, varies with time per thousand board feet; VMT, varies with milling time per thousand board feet; V Tot., varies with total of logging costs; CA, constant with area; V No., varies with the number of pieces per thousand board feet lumber tally; VP, varies with price of lumber.

[2] Labor $0.90.

[3] Labor $1.02.

[4] Towage was constant per thousand board feet lumber tally.

[5] Labor $1.

Similar trends are also disclosed by the production costs for logs.

The difference in production cost between small and large trees is emphasized here because it has an important bearing on the profits or losses that occur in handling trees of different sizes.

Because the volume of hardwoods in the stand was small, separate production-cost tables are not shown. For all practical purposes the hardwoods, diameter for diameter, may be considered as having the same production cost as the pine although, because there is a greater proportion of small diameters, the average is higher.

The production costs shown here are complete except for stumpage, Federal taxes, and interest. These are purposely excluded, and the spread between production cost and lumber value shown later is available to cover these items and provide a margin for profit.

LUMBER PRICES

Table 7 gives the prices of rough, dry lumber used in this study for loblolly pine and for the different hardwoods in the stand. These prices were obtained direct from the cooperating company's records and represent an average for 1929.

TABLE 7.—*Average prices of rough, dry, 1-inch loblolly pine and hardwood lumber per thousand board feet f. o. b. shipping point, northeastern North Carolina, 1929*

LOBLOLLY PINE

Widths	B and better	No. 1 and C	No. 1 box	No. 2 box	Bark strips	
					B and better	Box
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
4 inches	41.26	32.90	22.00	18.00	30	13
5 inches	43.00	33.70	22.00	18.00	30	13
6 inches	43.56					
7 and 8 inches	46.24	33.70	22.87	18.86	30	13
9 and 10 inches	50.00	37.00	23.90	19.86	30	13
11 and 12 inches	64.00	43.00	26.00	22.00	30	13

HARDWOOD

Species	F A S	No. 1 common	No. 2 common	No. 3 common
	Dollars	*Dollars*	*Dollars*	*Dollars*
Red gum [1]	45	35	18	15
Black gum or mixed oak		35	25	17

[1] Graded as sap gum.

GRADES AND VALUE OF LUMBER

The percentages of the different grades of lumber and the values as shown in Table 8 for loblolly pine trees and logs are for dry, rough lumber ready for the shipment. Changes due to drying and remanufacture have been taken into account and the green grades corrected accordingly. Table 9 gives the percentages of grades for hardwoods as established from a green-lumber tally. The value of the lumber when dry has been computed by applying a correction factor of 7 per cent, established in the course of earlier studies in the eastern hardwoods.

TABLE 8.—*Percentage of lumber by grades and value per thousand board feet, lumber tally, when dry for loblolly pine logs and trees of different diameters*

LOGS

Size in inches [1]	B and better		No. 1 and C		No. 1 box		No. 2 box		Bark strips				Average value of 1,000 board feet of dry lumber
									B and better		Box		
	Per cent	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Dollars*
5		40.97		32.24	86.5	21.89	10.0	17.93		30	4.4	13	21.10
6	0.2	41.22	1.5	32.34	83.6	21.94	10.2	17.98	0.3	30	4.2	13	21.38
7	.8	41.52	3.2	32.49	81.0	21.99	10.3	18.08	.7	30	4.0	13	21.78
8	1.9	41.81	4.9	32.58	78.0	22.09	10.4	18.18	1.1	30	3.7	13	22.32
9	3.0	42.21	6.7	32.73	75.0	22.24	10.5	18.28	1.4	30	3.4	13	22.92
10	4.9	42.61	8.5	32.88	71.5	22.39	10.4	18.43	1.7	30	3.0	13	23.71
11	7.7	43.25	10.3	33.03	67.4	22.64	10.0	18.63	2.0	30	2.6	13	24.79
12	11.0	44.04	12.3	33.42	63.0	22.93	9.3	18.92	2.2	30	2.2	13	26.11
13	14.1	44.94	13.3	34.40	60.2	23.43	8.2	19.27	2.4	30	1.8	13	27.55
14	15.9	45.88	13.6	35.72	58.8	23.98	7.8	19.82	2.5	30	1.4	13	28.73
15	17.0	47.17	13.8	37.24	57.9	24.58	7.6	20.37	2.5	30	1.2	13	29.84
16	17.8	48.11	14.0	38.22	57.5	25.27	7.4	20.87	2.4	30	.9	13	30.83
17	18.4	48.71	14.2	38.96	57.1	25.57	7.3	21.26	2.2	30	.8	13	31.41
Weighted average	7.9	44.56	9.0	33.90	68.4	22.74	10.1	18.65	1.8	30	2.8	13	24.92

TREES

8	0.2	41.27	3.1	32.24	76.3	21.89	14.4	17.93		30	6.0	13	21.15
9	.8	41.42	4.0	32.44	76.0	21.99	13.5	17.98	0.4	30	5.3	13	21.58
10	1.5	41.61	4.9	32.63	75.6	22.04	12.2	18.08	.9	30	4.9	13	22.00
11	2.6	41.96	6.0	32.78	75.2	22.14	10.6	18.13	1.3	30	4.3	13	22.58
12	4.0	42.36	7.2	32.88	74.6	22.24	8.9	18.18	1.5	30	3.8	13	23.21
13	5.6	42.80	8.4	32.98	72.7	22.34	8.2	18.28	1.7	30	3.4	13	23.86
14	7.4	43.35	9.7	33.12	69.9	22.49	8.2	18.38	1.8	30	3.0	13	24.58
15	8.9	44.00	10.5	33.47	67.3	22.64	8.7	18.53	1.9	30	2.7	13	25.20
16	9.8	44.59	10.4	33.96	66.1	22.84	9.3	18.63	2.0	30	2.4	13	25.64
17	10.5	45.24	9.7	34.59	65.4	23.08	10.2	18.77	2.0	30	2.2	13	26.00
18	10.8	45.98	9.1	35.38	64.4	23.38	11.8	18.97	1.9	30	2.0	13	26.31
19	10.4	46.57	8.3	35.87	63.2	23.68	14.5	19.22	1.8	30	1.8	13	26.35
20	9.1	47.02	7.5	36.26	62.1	23.88	17.9	19.42	1.7	30	1.7	13	26.03
21	7.3	47.37	6.7	36.55	61.4	24.08	21.5	19.57	1.6	30	1.5	13	25.57
22	6.6	47.47	5.7	36.51	60.8	24.28	24.3	19.62	1.4	30	1.2	13	25.32
Weighted average	7.9	44.56	9.0	33.90	68.4	22.74	10.1	18.65	1.8	30	2.8	13	24.92

[1] For logs, top diameter inside of bark; for trees, diameter breast high.

TABLE 9.—*Percentage of lumber by grades and value per thousand board feet for red gum [1] logs and trees by diameter classes*

LOGS

Top diameter inside bark, in inches	FAS	No. 1 common	No. 2 common	No. 3 common	Average value of 1,000 board feet of green lumber after seasoning [2]
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Dollars*
5				100.0	13.95
6		1.0	31.7	67.3	15.02
7		1.4	41.6	57.0	15.37
8		5.9	42.7	51.4	16.24
9		5.4	44.5	50.1	16.20
10	0.5	6.8	46.0	46.7	16.64
11		4.9	34.7	60.4	15.83
12	6.0	2.7	36.0	55.3	17.13
13		20.9	51.0	28.1	19.26
14	8.2	20.7	48.0	23.1	21.43
Weighted average	.7	5.7	42.6	51.0	16.39

[1] The average value of black gum was $17.42 per thousand board feet of green lumber.
[2] Value when dry obtained by reducing value when green 7 per cent to cover the loss by degrade and shrinkage during seasoning.

TABLE 9.—*Percentage of lumber by grades and value per thousand board feet for red gum logs and trees by diameter classes*—Continued

TREES

Diameter breast high, in inches	FAS	No. 1 common	No. 2 common	No. 3 common	Average value of 1,000 board feet of green lumber after seasoning
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Dollars*
8			53.3	46.7	15.44
9		1.6	39.2	59.2	15.34
10		2.4	39.2	58.4	15.49
11		6.0	46.9	47.1	16.38
12		4.3	42.2	53.5	15.93
13	0.5	8.7	39.6	51.2	16.81
14		3.3	40.4	56.3	15.63
15					
16	6.5	8.1	39.3	46.1	18.37
17		10.3	50.0	39.7	17.26
18		3.0	64.5	32.5	16.31
19	9.4	20.7	35.7	34.2	21.42
Weighted average	.7	5.7	42.6	51.0	16.39

Although this stand was about 80 per cent stocked, that the trees had not cleared themselves of their lower limbs early in life was evident from the low yield of only 7.9 per cent B and better. The trees in the largest diameter classes in this study, which were more or less open grown, showed less high-grade lumber than the trees several inches smaller in diameter that had grown in thicker stands.[5] This brings out the necessity for clearing the trunks of the trees of their lower limbs as early in life as possible. Close stocking, hardwoods in mixture, and limb pruning under favorable conditions are three ways by which this end may be gained. Generally, the larger and older the tree the greater the proportion of high-grade lumber. Small trees not only yield poorer quality lumber than large trees but, grade for grade, it is worth less because the average width is less. For example, in loblolly pine the B and better lumber from 9-inch trees is worth only $41.42 per thousand board feet, whereas that from 20-inch trees is worth $47.02. Taking all grades together, the average value of the lumber from 9-inch trees was $21.58 per thousand board feet, as compared with $26.03 for that from 20-inch trees. The increase in value as the trees become larger and the decrease in production costs when combined form the main economic argument for selective logging. By properly regulating the cutting the production costs can be held constant or reduced and the value of the product increased. Table 8 indicates that management of forest stands must take into account quality as well as quantity growth.

The quality and price trends for loblolly pine trees apply generally for logs. In addition to the effect of size on value, the position the log occupied in the tree also has an influence. Butt logs ordinarily yield higher quality lumber than the other logs in the tree (p. 18).

For the few hardwoods in the stand the same trend obtains as that shown for the pine, although the relationship among the different-sized logs and trees is not constant because of the small quantity of material studied and the poor quality of the trees. Table 9 gives the

[5] PAUL, B. H. THE RELATION OF CERTAIN FOREST CONDITIONS TO THE QUALITY AND VALUE OF SECOND-GROWTH LOBLOLLY PINE LUMBER. Jour. Forestry 30:4-21. 1932.

percentage of the different grades of lumber and the value by diameter classes for hardwood logs and trees.

In handling loblolly pine stands the necessity of growing wood of good quality as well as in satisfactory quantities must be kept in mind. There is a temptation to favor the pine and eliminate the hardwoods, which are not ordinarily of very good quality. It is probably satisfactory in the first cut to eliminate all but a small number of the best hardwoods. In subsequent cuts under management the hardwoods should improve in quality, and it is believed that they should be retained, in small volume at least, for the purpose of hastening the natural pruning of the pine and for improving the soil.

PRODUCTION COSTS AND LUMBER VALUES COMPARED

With production costs (excluding stumpage, Federal taxes, and interest on invested capital) and values available, it is possible to compare them and determine the realization for logs and trees of different diameters and for different cutting limits. It has been assumed that the permanent-improvement costs are the same for logs and trees of different sizes. Table 10 shows the production cost and lumber value for loblolly pine logs and trees. According to these figures a tree must be 11 inches in diameter to pay its way, not including stumpage, Federal taxes, interest, or profit, and a log must be 8 inches, if charged with all production costs. Logs less than 8 inches in diameter, however, may be taken to the mill, because below a certain size they need to bear only direct costs, owing to the custom of lumber companies of computing railroad and camp costs on the basis of the total volume, considering only a given size and larger. Small logs on the ground have no value unless utilized, whereas small logs in thrifty standing trees are valuable as growing stock and yield the best return if left growing.

TABLE 10.—*Difference between production cost and value of lumber per thousand board feet, lumber tally for loblolly pine logs and trees of different diameters*

Logs				Trees			
Top diameter inside bark in inches	Total lumber production cost	Value of lumber	Difference [1]	Diameter breast high	Total lumber production cost	Value of lumber	Difference [1]
	Dollars	*Dollars*	*Dollars*	*Inches*	*Dollars*	*Dollars*	*Dollars*
5	28.51	21.10	−7.41	8	30.17	21.15	−9.02
6	24.93	21.38	−3.55	9	27.05	21.58	−5.47
7	22.03	21.78	−.25	10	24.01	22.00	−2.01
8	19.79	22.32	+2.53	11	21.54	22.58	+1.04
9	18.25	22.92	+4.67	12	19.57	23.21	+3.64
10	17.12	23.71	+6.59	13	18.15	23.86	+5.71
11	16.41	24.79	+8.38	14	17.19	24.58	+7.39
12	15.76	26.11	+10.35	15	16.43	25.20	+8.77
13	15.21	27.55	+12.34	16	15.84	25.64	+9.80
14	14.76	28.73	+13.97	17	15.34	26.00	+10.66
15	14.33	29.84	+15.51	18	14.90	26.31	+11.41
16	13.98	30.83	+16.85	19	14.51	26.35	+11.84
17	13.71	31.41	+17.70	20	14.11	26.03	+11.92
				21	13.82	25.57	+11.75
				22	13.45	25.32	+11.87
Weighted average	16.94	24.92	+7.98		16.94	24.92	+7.98

[1] A minus sign indicates a loss.

For loblolly pine there was an average realization of $7.98 per thousand board feet, but it varied from a loss of $9.02 for 8-inch trees to a profit of $11.92 for 20-inch trees. This wide spread in realization is brought about by the decreased cost of handling large trees and their higher value as compared with small trees. The production cost with the portable band sawmill was from $1 to $2 less than that in the average large band sawmill and resulted in a smaller tree paying its way.

Table 10 also gives a clew to the stumpage price that an operator can afford to pay for trees of different sizes. If, for example, a company must have a 20 per cent margin for profit and risk, then the average stumpage value would be the production cost ($16.94) times 1.20, subtracted from the value of the lumber ($24.92), which leaves $4.59 as the average stumpage value for the stand as cut. Computing similarly, 10-inch trees have a minus stumpage value of $6.81 per thousand board feet as compared to a positive value of $9.10 for 20-inch trees.

The hardwoods on an average did not pay their way, since the value of the lumber was $16.46 per thousand board feet and the production cost $20.01 per thousand board feet. Because there is likely to be a loss or only a slight profit in handling small or defective hardwoods, there is a tendency to leave them standing, which is amply justified if the operator is interested in one cut only. If, on the other hand, it is desired to grow successive crops of timber on the land, the space occupied by poor hardwoods must be released to pine or good-quality hardwoods if the maximum return from the land is to be realized. While all the hardwoods were cut into lumber during the study, the company ordinarily utilized as much of this material as possible in its own operation for ties and similar products. Some attempts had also been made to sell the hardwoods for pulpwood. In view of the loss incurred in cutting them into lumber, the problem of finding some method of disposing of the poorer hardwoods at least at a price equal to the cost of cutting them needs immediate solution. With fire protection and management, hardwoods in old-field pine stands should develop in time into fairly good quality trees, so that the present problem would not be perpetual in handling such stands. It may oftentimes be practicable to remove many of these poor-quality trees by thinning, girdling, or poisoning operations. Thrifty, sound hardwood trees of valuable species in mixture with loblolly pine are desirable according to the best information available, and in long-time plans may be allowed to make up 10 to 20 per cent of the stands.

A consideration of the comparative returns and grades of lumber obtained from trees of different sizes should be supplemented with similar information on logs of different sizes and position in the tree. Table 11 has been prepared to supply such information. The logs were divided into three quality classes based largely on their original position in the tree. In studying the results shown here the difference between small logs from small thrifty trees and small logs from the tops of large trees should be kept in mind (p. 17). As might be expected, there is some overlapping of quality and value in logs of the same diameters but from different positions in the tree, yet the three quality classes, on an average, are separated by a spread of $3.56 per thousand board feet between butt and middle logs and $2.97 between middle and top logs.

TABLE 11.—*Percentage of lumber by grades, value per thousand board feet of dry lumber, and production cost of loblolly pine logs of different diameter and quality*

BUTT LOGS

Top diameter inside bark in inches	B and better		No. 1 and C		No. 1 box		No. 2 box		Bark strips				Average value	Production cost	Difference [1]
									B and better		Box				
	Per cent	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
6	-------	41.35	4.0	32.90	78.3	22.00	12.2	18.00	-------	30	5.5	13	21.45	25.26	−3.81
7	1.2	41.50	6.4	32.90	74.0	22.08	11.6	18.03	1.5	30	5.3	13	22.17	22.96	−.79
8	3.7	41.75	8.8	32.90	69.8	22.15	10.9	18.09	1.9	30	4.9	13	23.08	20.69	+2.39
9	6.3	42.15	11.5	32.95	65.5	22.27	10.0	18.15	2.3	30	4.4	13	24.11	19.20	+4.91
10	9.7	42.70	13.8	33.00	61.3	22.40	9.0	18.25	2.6	30	3.6	13	25.32	17.95	+7.37
11	13.3	43.45	15.5	33.10	57.4	22.65	8.1	18.40	2.9	30	2.8	13	26.63	17.00	+9.63
12	15.5	44.30	16.7	33.60	55.4	23.00	7.3	18.70	3.1	30	2.0	13	27.77	16.13	+11.64
13	17.5	45.20	17.0	34.60	54.4	23.45	6.6	19.15	3.1	30	1.4	13	28.92	15.35	+13.57
14	18.8	46.15	16.7	35.70	54.7	23.95	6.0	19.70	2.9	30	.9	13	29.91	14.68	+15.23
15	19.7	47.10	13.7	36.90	57.4	24.50	5.3	20.30	2.6	30	1.3	13	30.42	14.19	+16.23
16	20.4	48.15	10.5	38.00	61.9	25.03	4.9	20.95	2.3	30	-------	-------	31.02	13.81	+17.21
17	20.9	49.30	7.0	39.20	65.6	25.60	4.5	21.60	2.0	30	-------	-------	31.41	13.23	+18.18
Weighted average	14.2	44.97	14.3	34.25	58.7	23.09	7.4	18.75	2.8	30	2.6	13	27.40	16.72	+10.68

MIDDLE AND OTHER LOGS WITH FEW SMALL KNOTS

5	-------	40.58	-------	32.52	85.9	22.00	9.9	18.00	-------	30	4.2	13	21.23	25.77	−4.54
6	-------	40.70	2.2	32.60	83.7	22.00	10.0	18.00	0.1	30	4.0	13	21.48	23.30	−1.82
7	0.2	41.09	3.5	32.65	81.8	22.00	10.3	18.06	.4	30	3.8	13	21.70	21.29	+.41
8	.7	41.37	5.0	32.72	79.5	22.20	10.5	18.12	.7	30	3.6	13	22.16	19.35	+2.81
9	1.6	41.90	6.2	32.80	77.0	22.47	10.8	18.23	1.0	30	3.4	13	22.72	17.82	+4.90
10	3.2	42.38	7.4	32.92	73.9	22.80	11.1	18.40	1.3	30	3.1	13	23.48	16.63	+6.85
11	5.4	42.93	8.6	33.08	70.2	23.30	11.5	18.60	1.5	30	2.8	13	24.47	15.77	+8.70
12	7.2	43.60	9.7	33.35	66.7	24.00	12.2	18.85	1.8	30	2.4	13	25.53	15.02	+10.51
13	8.4	44.40	10.6	33.87	63.6	24.90	13.4	19.20	2.0	30	2.0	13	26.59	14.41	+12.18
14	9.2	45.40	11.4	34.70	60.7	26.00	15.0	19.69	2.2	30	1.5	13	27.72	13.86	+13.86
15	9.9	46.50	12.0	35.80	57.9	27.30	16.7	20.38	2.5	30	1.0	13	28.99	13.34	+15.65
Weighted average	3.9	43.56	7.5	33.31	73.4	23.10	11.2	18.55	1.2	30	2.8	13	23.95	16.83	+7.12

[1] A minus sign indicates a loss.

TABLE 11.—*Percentage of lumber by grades, value per thousand board feet of dry lumber, and production cost of loblolly pine logs of different diameter and quality*—Continued

TOP LOGS AND OTHER LOGS WITH COARSE OR MANY SMALL KNOTS

Top diameter inside bark in inches	B and better		No. 1 and C		No. 1 box		No. 2 box		Bark strips				Average value	Production cost	Difference
									B and better		Box				
	Per cent	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
5	-------	40.50	-------	32.90	92.6	22.00	2.5	18.00	-------	30	4.9	13	21.46	24.82	−3.36
6	-------	40.80	0.3	32.90	89.8	22.06	5.3	18.00	-------	30	4.6	13	21.46	23.22	−1.76
7	0.3	41.20	.4	32.95	86.4	22.10	8.5	18.05	-------	30	4.4	13	21.46	21.49	−.03
8	.3	41.70	.4	33.04	83.6	22.19	11.5	18.10	-------	30	4.2	13	21.44	19.75	+1.69
9	.3	42.27	.7	33.15	80.1	22.28	14.5	18.20	0.4	30	4.0	13	21.48	18.29	+3.19
10	.3	42.88	1.4	33.30	76.4	22.38	17.7	18.34	.4	30	3.8	13	21.55	17.04	+4.51
11	.4	43.60	2.4	33.50	72.3	22.50	21.0	18.58	.4	30	3.5	13	21.72	16.24	+5.48
12	.4	44.30	3.5	33.75	68.2	22.65	24.2	18.90	.4	30	3.3	13	21.93	15.55	+6.38
13	.4	45.02	4.6	34.00	64.0	22.82	27.5	19.34	.4	30	3.1	13	22.19	14.94	+7.25
14	.5	45.80	5.8	34.29	60.3	23.06	30.0	19.82	.5	30	2.9	13	22.60	14.35	+8.25
15	.5	46.55	6.9	34.58	56.0	23.35	33.3	20.38	.6	30	2.7	13	23.01	13.98	+9.03
Weighted average	.4	44.25	1.3	33.56	78.1	22.34	16.5	18.61	.4	30	3.3	13	21.68	17.53	+4.15

The information in Table 11 should be useful to the operator in determining his top cutting limits and to the log buyer and seller in obtaining an idea of the comparative value of logs of the same size but from different positions in the tree. A top log, if charged with all production costs, had to be about 7 inches in diameter to pay its way, not including stumpage or Federal taxes. If the railroad-construction charges are carried by the larger logs, as is often the case, 6-inch logs would nearly pay their way. If the small logs had been sawed into scantlings instead of lumber, the returns under ordinary conditions would have been larger.

RETURNS FROM DIFFERENT DIAMETER CUTTING LIMITS

To illustrate the economic side of selective logging, it is desirable to consider the returns when cutting to different diameter limits. In using these data it must be kept in mind that a rigid diameter limit is not advocated and in most cases would not be good practice. Trees below the limit should be cut if of poor form and thrift, and trees above the limit should be left if needed for seed production or to increase the yield of the second cut.

Table 12 shows the results if the loblolly pine in the stand were cut to different diameter limits. If all trees 8 inches in diameter and larger were cut, 20,770 board feet of lumber would be removed and the gross returns per acre would be $129.19. To compute the net returns, stumpage, interest, and Federal taxes would have to be deducted from this figure. These items are so variable that no attempt is made here to give figures for them. If the 8, 9, and 10 inch trees are left uncut the gross returns become $137.02 per acre. That is, by cutting only trees 11 inches in diameter and larger the highest return per acre is obtained. The highest return per thousand board feet, however, is obtained when only trees 15 inches and larger are cut. This indicates that the owner interested in a return cut would do well to adhere to the 15-inch cutting limit, whereas an operator who has purchased timber only with the privilege of taking what he desired might take out trees as small as 11 or 12 inches. From the standpoint of both the landowner and the operator, leaving the small trees uncut is an advantage, for by cutting only trees 11 inches in diameter and larger, as compared with cutting to an 8-inch limit, the operator prevents a loss of $7.83 per acre and the landowner saves 2,929 board feet of small timber to stock the land and grow into a second cut. Under such a plan, however, it would be a long time before another cut would be possible. By leaving all trees 13 inches in diameter and smaller, 9,513 board feet, lumber tally, per acre would remain, and a return cut could be made to advantage in 10 years.

TABLE 12.—*Total production costs,*[1] *lumber value, and gross returns per thousand board feet, lumber tally, and per acre for loblolly pine by cutting to different diameter limits*

Cutting to a diameter limit breast high of—	Value of lumber	Total lumber-production cost	Difference	Cut per acre	Gross returns per acre [2]
	Dollars	*Dollars*	*Dollars*	*Board feet*	*Dollars*
8 inches and up	24.26	18.04	6.22	20,770	129.19
9 inches and up	24.35	17.77	6.58	20,147	132.57
10 inches and up	24.47	17.42	7.05	19,316	136.18
11 inches and up	24.68	17.00	7.68	17,841	137.02
12 inches and up	24.94	16.59	8.35	15,827	132.16
13 inches and up	25.21	16.37	8.84	13,729	121.36
14 inches and up	25.52	16.29	9.23	11,257	103.90
15 inches and up	25.75	16.45	9.30	8,890	82.68
16 inches and up	25.97	17.03	8.94	6,356	56.82
17 inches and up	26.13	18.27	7.86	4,320	33.96
18 inches and up	26.21	21.13	5.08	2,617	13.29

[1] Includes all costs except stumpage, interest, and Federal taxes.
[2] Available to cover profit, stumpage, interest, and Federal taxes.

Table 12 shows that the production cost under selective logging does not increase but actually decreases until the 15-inch diameter cutting limit is reached. This is conservative, since in an established selective logging operation costs for railroads and camps would not increase so rapidly, because old grades and roads could be used over and over, while in the foregoing example no such credit has been taken into account.

So far results for the pine only have been given, but in managing the stand for permanent timber production some consideration must be given to the hardwoods. The most logical thing to do is to cut the poor hardwoods along with the pine. This was done, and the results are shown in Table 13, together with a diameter-cutting limit for the pine. Since, as previously pointed out, the hardwoods did not pay their way, the returns are less than for pine alone. For example, if all trees 8 inches and larger, both hardwoods and pine, are cut, the gross returns per acre would be only $122.52, as compared with $129.19 for the pine alone. If all the hardwoods 8 inches in diameter and larger and only the pine 11 inches and larger are cut, the gross return is $131.35, whereas the pine alone yields $137.02. These examples indicate that the removal of the hardwoods actually caused a loss, but over a long time this would be made up by an increased volume of pine. From this comparison it must not be taken for granted that all the hardwoods should be cut, for good-quality hardwood in small amounts in a pine stand is believed to be beneficial; and if fire is kept out, it should pay its way. For the first cut, however, a slight loss will probably be incurred in clearing the area of undesirable hardwoods.

TABLE 13.—*Total production cost, value of lumber, and gross returns per thousand board feet, lumber tally, and per acre by cutting all hardwoods and the loblolly pine to different diameter limits*

Cutting to a diameter limit breast high of—	Volume removed per acre		Value of lumber	Total [2] production cost	Difference	Gross returns per acre [3]
	Loblolly pine	Hardwoods [1]				
	Board feet	*Board feet*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
8 inches and up	20,770	1,306	23.80	18.25	5.55	122.52
9 inches and up	20,147	1,306	23.87	17.95	5.92	127.00
10 inches and up	19,316	1,306	23.97	17.64	6.33	130.54
11 inches and up	17,841	1,306	24.12	17.26	6.86	131.35
12 inches and up	15,827	1,306	24.30	16.93	7.37	126.27
13 inches and up	13,729	1,306	24.45	16.78	7.67	115.32
14 inches and up	11,257	1,306	24.57	16.82	7.75	97.36
15 inches and up	8,890	1,306	24.56	17.08	7.48	76.27
16 inches and up	6,356	1,306	24.35	17.79	6.56	50.26
17 inches and up	4,320	1,306	23.89	19.04	4.85	27.29
18 inches and up	2,617	1,306	22.96	21.28	1.68	6.59

[1] The volume removed is constant because in a selective-logging plan favoring pine the present hardwoods should be removed.
[2] Includes all costs except stumpage, interest, and Federal taxes.
[3] Available for profit, stumpage, interest, and Federal taxes.

Under the selective-logging plan carried out in this study, all the merchantable hardwoods 8 inches in diameter and larger were cut and 69 per cent of the total volume of the pine, which was made up of trees from 8 to 22 inches in diameter. Only 7.5 per cent of the cut, however, came from trees less than 12 inches in diameter.

Under management the next cut of pine will be made up of better-quality trees than the present one. and there should be fewer hardwoods of low value.

APPLICATION OF RESULTS TO UTILIZATION AND FOREST PRACTICE IN NORTH CAROLINA

Competition in the lumber industry has become so keen that the producer, if he is to continue in the business, must take advantage of every opportunity to increase the revenue obtainable. Higher stumpage and lumber prices and an increasing demand for forest products can not be depended upon to carry him along. Closer utilization carried out in a practical way is one of the best ways of getting more revenue from the forest. The use of the portable band saw described in this bulletin is a forward step in utilization. At this operation the waste due to sawdust was reduced about one-third of that common with large band saws. In addition the lumber was kiln-dried before being edged, then edged to random widths, thus increasing the amount of lumber that a given log would yield as compared with the results where the lumber is edged while green and cut to stock widths.

Easy portability of woods and mill equipment adds materially to the success of selective-logging operations, since it is necessary to cover a larger area to obtain a given amount of timber than under clear cutting. Although the operation studied was carried on by the use of railroads, the mill, with some modification, can be mounted on trucks to travel on ordinary roads. For small tracts of timber such a mill would have many advantages.

With a thin saw and a market for bark strips it is possible to reduce the waste in slabs to a minimum. Furthermore, in this operation the edgings were dry and ready to be manufactured into molding, handles, and dimension stock without further drying or handling.

The lumber was well manufactured at this portable band sawmill, and the loss from thick and thin lumber and lumber of nonuniform thickness was reduced to a practicable minimum.

Before attempting to apply the methods set forth in this bulletin, each individual company should determine (1) whether it desires to make its operation permanent and (2) whether it can do so. Such a decision rests primarily on whether the owners expect to stay in the lumber business or other wood-using industry, whether sufficient land is owned and enough timber is available to make possible a permanent operation, and whether the financial condition of the company permits of carrying on such an undertaking. No nation-wide recommendation can be made. It is certain, however, that there are thousands of acres in the coastal plain better suited at present to raising trees than other crops, that higher yields of timber are obtained under management and fire protection than under unregulated cutting with little or no fire protection, and that loblolly pine grows rapidly and has a wide and ready market both here and abroad.

The best information indicates that selective logging is a practicable way of cutting loblolly pine stands. No matter whether the area is large or small this method of cutting can be used. For the farm wood lot or the small area of timberland selective cutting is especially to be considered, because these areas are usually easily accessible and can be logged at any time with moderate or practically no direct cost for roads. Improved highways and the development of motor trucks have made it practicable to market either logs or lumber successfully even though the haul is as great as 20 to 30 miles.

Practically none of the loblolly pineland is producing all the wood it is capable of producing, because there are not enough trees on it. Timberland owners when embarking on selective cutting will have to work with less than fully stocked stands and must, therefore, be content with less than maximum growth until their timber can be improved by management and fire protection to a point where the land is stocked with all the thrifty well-formed trees it will support. The area studied was about four-fifths stocked with timber 4 inches and larger, which may be accepted as representative of old-field timber on the better sites. It is interesting to compute the returns for such a stand for the next two cutting cycles, assuming that selective cutting will be practiced and fire kept out. Table 14 shows the actual amount of timber per acre that was cut from the study area under selective logging, the average production cost and lumber value, and the gross returns per acre. In addition the same information is given for two cuts in the future, assuming comparable production costs and lumber values and a growth rate of 1 inch in diameter in five years, which is about 15 per cent slower growth than that of the average tree in the original stand.

TABLE 14.—*Probable gross returns per acre for loblolly pine under selective cutting at 20-year intervals*

Diameter breast high in inches	Trees per acre			Volume per acre dry lumber tally		20 years after first cut		40 years after first cut	
	Standing	Cut	Left	Left	Cut	Trees per acre [1]	Volume per acre dry lumber tally [2]	Trees per acre	Volume per acre dry lumber tally [2]
	Number	*Number*	*Number*	*Board feet*	*Board feet*	*Number*	*Board feet*	*Number*	*Board feet*
3	0.9		0.9						
4	1.1	0.2	.9						
5	1.4	.5	.9						
6	5.8	1.0	4.8						
7	14.1	3.0	11.1			0.9			
8	18.4	4.0	14.4	488	135	.9			
9	23.7	4.5	19.2	673	158	.9			
10	23.7	6.0	17.7	1,102	373	4.8			
11	22.0	8.4	13.6	1,245	769	11.1		0.9	
12	17.5	10.0	7.5	899	1,199	14.4		.9	
13	15.9	10.7	5.2	808	1,664	19.2		.9	
14	12.7	9.2	3.5	652	1,715	8.7 9.0	1,510	4.8	
15	11.0	9.6	1.4	323	2,211	13.6	2,820	11.1	
16	7.4	6.6	.8	220	1,816	7.5	1,857	14.4	
17	5.2	4.9	.3	98	1,605	5.2	1,533	19.2	5,659
18	3.2	3.2			1,184	3.5	1,166	8.7	2,897
19	2.2	2.2			851	1.4	487		
20	.9	.9			333	.8	266		
21	.5	.5			207	.3	112		
22	.1	.1			42				
Total	187.7	85.5	102.2	6,508	[3] 14,262		9,751		8,556
					Dollars		*Dollars*		*Dollars*
Lumber value per thousand board feet					24.92		25.53		26.10
Production cost per thousand board feet					16.94		15.89		15.19
Difference per thousand board feet					7.98		9.64		10.91
Gross returns per acre					111.53		94.00		93.35

[1] Under forest management the diameters below 7 inches should be filled in by young trees.
[2] A reduction of 10 per cent is made for loss from windfall, disease, and the like. Values represent volumes above diameter cutting limits.
[3] Includes 286 board feet lost in logging.

The cut as made yielded 14,262 board feet per acre, 13,976 board feet of which came into the mill and resulted in a gross return of $111.53 to cover stumpage, profit, interest, and Federal taxes. If the remaining trees grow at the rate of 1 inch in 5 years, then in 20 years it would be possible to cut with a portable band sawmill 9,751 board feet per acre and obtain a gross return of $94. Similarly, 40 years after the first cut 8,556 board feet could be removed which would yield a gross return of $93.35. With fire protection and average rainfall the area should have seeded, and a stand approaching full stocking should be growing on the land, making a satisfactory return cut available every few years for all time. To some, the interval between cuts may seem too long, and it would be entirely practicable to return every 10 years if the operator is satisfied with a smaller yield per acre. With portable-mill equipment it is entirely practicable to log areas where the cut is only 1,000 to 2,000 board feet per acre, so that it seems probable that short rotations will obtain in many permanent small mill operations. A diameter limit has been used in Table 14 to indicate the results for the two future cuts in the absence of definite figures on selective cutting. In practice the stand should be logged about as indicated by the cut that was made during the study. Only thrifty, well-formed trees should be left uncut so that the quality of the trees occupying the land will improve with time.

If a company desired to operate in a small way and run three of the portable mills similar to the ones described in this bulletin, it would need about 7,000,000 board feet of logs annually. About 17,500 acres of loblolly pineland would be required to grow that amount of timber if an average growth of 400 board feet of lumber could be attained. Taking the land as it would occur in a block of such size probably this estimate of growth is too high for the first several cutting cycles, and it might therefore be necessary to increase the acreage in order to maintain the foregoing output.

LOG GRADES

Many mills in the coastal plain buy logs from farmers and wood-lot owners, but there are no generally recognized and accepted rules for separating the logs into quality classes or grades. To assist in development of such grades, all the logs in this study were classified according to a tentative set of rules which follow:

NO. 1 LOGS

Surface-clear logs from 14 to 15 inches and logs 16 inches and over in diameter inside bark, small end, which contain not to exceed three 2 to 4 inch knots. Reasonably straight grained. Length 10 feet and over.

NO. 2 LOGS

Surface-clear logs 6 to 10 inches in diameter and larger containing numerous small knots or more knots than allowed in grade No. 1. Length 8 feet and over.

NO. 3 LOGS

Coarse, knotty, crooked logs that do not fall in either grades No. 1 or No. 2. No limitations on size or quality of lumber produced.

NO. 4 LOGS

All logs that are less than one-third sound.

Table 15 shows the results of the study and indicates the net value ln logs of different grades taking into account the variation in overrun as well as the difference in quality.

TABLE 15.—*Value of loblolly pine logs by grades for use in purchasing and selling*

Log grade No.	Description of log grades	Contents (lumber tally) of the average log	Overrun	Average value of the dry lumber in 1,000 board feet [1] of logs	Production costs per 1,000 board feet [1] from log deck to shipping platform	Difference between value and log deck to shipping platform cost per 1,000 board feet [1]	Average value of 1,000 board feet [1] of dry lumber
		Board feet	*Per cent*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
1	Surface-clear logs 14 and 15 inches in diameter. Logs 16 inches in diameter and over, but having not more than three knots	136	17.1	36.73	11.68	−25.05	31.37
2	Surface-clear logs 6 to 10 inches in diameter. Larger logs with small knots	77	41.5	36.83	12.94	−23.89	26.03
3	Coarse, knotty, crooked logs	41	92.8	43.01	15.30	−27.71	22.31
4	Logs that are less than one-third sound	[2]	[2]	[2]	[2]	[2]	[2]

[1] Gross scale Doyle.

[2] Cull.

Owing to the extremely high overrun that obtained for the No. 3 logs, the lumber in a thousand board feet gross scale of logs was worth more than for the higher grade No. 1 logs. On a thousand-foot lumber-tally basis, however, the lumber from the No. 1 logs was worth $9.06 more than that from the No. 3 logs. In addition the cost of cutting the No. 1 logs, which averaged 136 board feet each, into lumber was less per thousand board feet than for the No. 3 logs, which ran only 41 board feet per log.

From Table 15 it is possible for a millman to determine the price he can pay for logs of a given grade and average size and yet make a profit of a given amount. Suppose a deck of logs were offered to a millman at a given price. He could classify the logs and then by reference to Table 14 determine that the lumber in No. 1 logs, at the prices obtaining during the study, was worth $31.37 per thousand board feet and that the overrun would be about 17.1 per cent. Suppose his milling cost and margin for profit for logs of this size amounted to $14. Under these conditions he could afford to pay $20.34 per thousand board feet gross log scale (overrun per cent of 1.171 times $31.37 minus 1.171 times $14). Similarly, with a production cost and profit charge of $18, he could afford to pay about $8.31 per thousand board feet log scale for No. 3 logs. These data are based on 2,000 logs and should be representative.

Table 16 is for the use of the log buyer or seller who wishes to set up a value for his logs using different lumber prices from those obtained in this study. The grade percentages indicate a reasonable separation into quality classes. For example, grade No. 1 logs contain 22.2 per cent B and better, No. 2 logs 10.7 per cent, and No. 3 logs only 1.6 per cent. There is also a good spread in value, No. 1 logs being worth $5.34 more per thousand board feet than No. 2 logs and $9.06 more than No. 3 logs. Cull logs vary so widely in value that no attempt has been made to evaluate them.

TABLE 16.—*Quality and value of dry lumber from loblolly pine logs of different grades*

Lumber grade	No. 1 logs		No. 2 logs		No. 3 logs	
	Dry lumber	Value per M feet b. m.	Dry lumber	Value per M feet b. m.	Dry lumber	Value per M feet b. m.
	Per cent	*Dollars*	*Per cent*	*Dollars*	*Per cent*	*Dollars*
B and better	22.2	47.13	10.7	44.13	1.6	42.78
No. 1 and C	15.8	36.90	12.9	33.62	4.4	32.85
No. 1 box	56.7	24.18	62.1	22.75	77.5	22.27
No. 2 box	1.8	20.77	9.3	19.04	12.7	18.31
B and better bark strips	2.6	30.00	2.5	30.00	.6	30.00
Box bark strips	.9	13.00	2.5	13.00	3.2	13.00
Total or weighted average	100.0	31.37	100.0	26.03	100.0	22.31

In the old-field loblolly pine stand covered by this study 9.6 per cent of the logs graded No. 1, 54.1 per cent No. 2, 35.9 per cent No. 3, and 0.4 per cent No. 4 on the basis of gross log scale.

VOLUME AND VALUE OF INDIVIDUAL LOBLOLLY PINE TREES

Table 17 gives the average volume and value for trees of different diameters. For example, 10-inch trees have an average volume of 62 feet, board measure, and a value of $1.36, but production costs are $1.49, so that such trees result in a loss of $0.13 each, whereas 20-inch trees have a volume of 370 board feet and a value of $9.63, which is sufficient to cover production costs and leave a balance of $4.41 to cover stumpage, interest, Federal taxes, and profit. The figures in Table 17 should be useful in determining the value of individual trees in connection with the marking of a stand for selective cutting and in sales of trees from wood lots.

TABLE 17.—*Average volume and value of old-field loblolly pine trees of different diameters*

Diameter breast high	Volume of dry lumber per tree	Cost of cutting each tree into lumber	Value of lumber in each tree	Difference	Stumpage [1] value of each tree
Inches	*Board feet*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
8	34	1.03	0.72	−0.31	−0.52
9	35	.95	.76	−.19	−.38
10	62	1.49	1.36	−.13	−.43
11	92	1.98	2.08	+.10	−.30
12	120	2.35	2.79	+.44	−.03
13	155	2.81	3.70	+.89	+.33
14	186	3.20	4.57	+1.37	+.73
15	230	3.78	5.80	+2.02	+1.26
16	275	4.36	7.05	+2.69	+1.82
17	328	5.03	8.53	+3.50	+2.49
18	370	5.51	9.73	+4.22	+3.12
19	387	5.62	10.20	+4.58	+3.46
20	370	5.22	9.63	+4.41	+3.37
21	414	5.72	10.59	+4.87	+3.73
22	420	5.65	10.63	+4.98	+3.85

[1] Stumpage value is the production cost, plus a 20 per cent margin for profit, subtracted from the value of the lumber.

CONCLUSIONS

The following conclusions are drawn from a study of the use of portable band sawmills in the selective logging of an old-field second-growth loblolly pine stand in North Carolina:

Portable band sawmills were operated successfully with a full-time filer in the woods to take care of the saws for a group of three mills.

The portable band sawmills studied put out well-manufactured lumber and obtained more lumber from logs of a given size than did a large band sawmill in the same locality.

Edging and trimming the lumber after it had passed through the kiln worked out satisfactorily.

Partial cutting, or selective logging, proved a satisfactory economic method of logging old-field loblolly pine stands in the coastal plain.

Production costs were lower under selective cutting than under clear cutting until a high diameter limit was reached.

The greatest gross return was obtained from the least volume; that is, a 14-inch cutting limit removed 54 per cent of the volume and yielded 76 per cent of the highest possible return.

Loblolly pine trees under 11 inches in diameter did not pay their way when cut into lumber, not including the cost of stumpage, Federal taxes, or interest. If these items are included, a tree would need to be at least 13 inches in diameter to pay its way.

The small hardwoods cut in this operation did not pay their way.

A logger who has no interest in establishing a permanent operation and who has the same costs as obtained at the operation studied would make the most money per acre by cutting only trees 11 inches in diameter and larger.

Inasmuch as an old field produced a stand 80 per cent stocked without management and with only partial fire protection, the chances of obtaining full stocking under management and complete fire protection are good.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Forest Service	R. Y. STUART, *Chief.*
Branch of Research	EARLE H. CLAPP, *Assistant Forester, in Charge.*
Forest Products Laboratory	CARLILE P. WINSLOW, *Director.*
Section of Industrial Investigations	C. V. SWEET, *Principal Engineer, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN NO. 336 DECEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

ATTRACTANTS FOR THE FLYING GIPSY MOTHS AS AN AID IN LOCATING NEW INFESTATIONS

By C. W. COLLINS, *Senior Entomologist*, and S. F. POTTS, *Assistant Entomologist, Division of Forest Insects, Bureau of Entomology*[1]

CONTENTS

	Page
Introduction	1
Types of cages and marking and liberation of males	3
Living female moths as source of attraction	5
Flight of males and proportion finding females	6
Distances males fly in seeking females	8
Distances males fly in confinement	9
Tests of trapping males on a large scale	10
Recovery experiments with extracts in Maine	12
Chemical studies of the attracting substance	14
Test for acid	17
Hydrolysis with acid	18
Test for base	18
Test for unsaturated compounds	18
Test for aldehydes	18
Chemical studies of the attracting substance—Continued	
Volatility tests	18
Thermal test	19
Anatomical studies	20
Tests of extracts	23
Experiments from 1920 to 1927	23
Experiments in 1928	28
Experiments in 1929	31
Results with various absorbent materials	32
Test of age of females	33
Results of other tests at Saugus, Mass	35
Obtaining female abdominal tip material	36
Use of extracts to locate new infestations in New England	39
Use of extracts in New Jersey	41
Summary	42

INTRODUCTION

Experiments with attractants for the male of the gipsy moth, *Porthetria dispar* L., were begun with the hope of reducing infestations by attracting the males in a given area to traps containing caged females, thus leaving the females in the area unfertilized. Though this idea seemed plausible, the plan was not successful, and the work was directed toward the following objectives: (1) To locate new infestations as an aid to scouting and eradication work, (2) to study the flight and habits of the male moths, (3) to substitute extracts of female "tips"[2] for living females in the traps, thus elimi-

[1] The writers are indebted to A. F. Burgess for general direction and suggestions while he was connected with the Bureau of Entomology, and for continued cooperation since his connection with the Bureau of Plant Quarantine; and to H. L. Blaisdell, S. S. Crossman, and H. A. Ames, of the Bureau of Plant Quarantine, for their hearty cooperation and assistance. L. H. Worthley and H. L. McIntyre, formerly of the Bureau of Entomology, assisted in the execution of some of the large field experiments. Several workers at the gipsy-moth laboratory, Melrose Highlands, Mass., gave valuable assistance, especially C. E. Hood. J. E. R. Holbrook, R. Wooldridge, P. B. Dowden, D. F. Barnes, R. L. Wallis, R. R. Whitten, and F. W. Graham (formerly of the Bureau of Entomology). E. P. Kohler, professor of organic chemistry at Harvard University, rendered valuable cooperation in connection with the chemical studies, as did also three other chemists mentioned in connection with their reports.

[2] "Tip" refers to the posterior end of the abdomen comprising the last segments and genitalia.

nating the danger of starting new infestations in a possibly free area, (4) to locate the organ or glands which produce the attracting substance, (5) to determine the possibility of isolating, studying, and producing the attractive substance in quantity synthetically and cheaply, and (6) to determine the value of this information for work on other insect species.

Though considerable has been written on the sense of smell in mammals, this subject has been much less thoroughly investigated than have the senses of sight, hearing, and touch. Taste, which is associated with smell, has likewise received relatively little attention. The sense of smell is continually employed throughout most of the animal kingdom, in connection with obtaining food, protection, recognition, communication, and mating. Studies of the sense of smell in insects have, for the most part, been centered on recognition, as among the bees and ants, or in connection with taste as related to obtaining food. It has been known for centuries that male moths may be attracted from a distance by females of the same species, but this fact has been mainly taken for granted and has been given very little detailed study.

The female gipsy moth does not fly, but the male is a strong flier and is able to locate the female by means of scent. The scent is given off from the vicinity of the vaginal opening of the female and is picked up by the male through its antennae. The male proceeds to find the female by means of zigzag flight, usually against the wind carrying the scent. According to Forbush and Fernald [3] the male antennae are very strongly bipectinated, the pectinations being somewhat curved, and tapering slightly toward the outer end, where they terminate in a tooth on one side, and a much longer spine on the other. In the female the pectinations are very much shorter and stouter.

To ascertain whether any advantage could be taken of these habits by attracting the males to traps containing unfertilized females, A. H. Kirkland began some experiments in eastern Massachusetts in 1893,[4] which were continued by H. N. Reid, to determine whether it were possible to trap enough males in a heavy infestation to reduce the fertilization of eggs enough so that a marked reduction in the number of moths and the degree of infestation could be expected the following season. These experiments were carefully planned and executed, but as a final result only 2.4 per cent of the egg clusters deposited in the area where the traps were exposed proved to be infertile. Since some infertile eggs are generally found in gipsy-moth infestations, this percentage has little significance.

Up to 1913 the area infested by the gipsy moth had continued to increase, and isolated colonies were sometimes found in unexpected places well beyond the supposed border of infestation. Such colonies were difficult and expensive to locate by scouting without clues as to their location or existence. A. F. Burgess, at that time in charge of the gipsy-moth investigations for the Bureau of Entomol-

[3] Forbush, E. H., and Fernald, C. H., The Gypsy Moth. (Porthetria dispar Linn.) A report of the work of destroying the insect in the commonwealth of Massachusetts together with an account of its history and habits both in Massachusetts and in Europe. P. 339–340. Boston. 1896.

[4] Forbush, E. H., and Fernald, C. H. Op. cit., p. 345–363.

ogy, decided that some experiments should be conducted to facilitate finding these colonies, and the senior writer took up the investigations at that time.

TYPES OF CAGES AND MARKING AND LIBERATION OF MALES

The first cage used in 1913 was made from a wooden box 15 by 4 by 4 inches. The top and bottom were replaced with a double wall of 20-mesh wire screening with one-half inch space between walls to prevent mating by the inclosed females with males that might be attracted to the cages. Later, when a large number of these cages were required for use in border territory infested by the gipsy moth, it was necessary to reduce the size, and accordingly a cage 5 by 3½ inches made of ½-inch wood stock, with a clearance space between top and bottom of 1¾ inches, was found advantageous. A covered circular hole 1½ inches in diameter in the top served for the introduction of female pupae, or moths. A wooden strip of ½-inch stock served to hold the top and bottom together and to attach the cage to a tree. Double walls one-half inch apart made of fly wire screen composed the four sides. This insured good circulation of air to carry the scent and yet prevented mating with outside males. (Fig. 1.)

FIGURE 1.—Type of cage used in early experiments and as check cages to hold living females of the gipsy moth. The illustration shows the trap number and the males caught in the sticky material in a single day

After it was found that males could be attracted by means of an extract from the tips of abdomens of females, a 3-ounce tin salve box (fig. 2) was used as a container. From four to six small holes, in pairs or groups of three, were drilled in each side of the tin for the passage of air to evaporate the solvent and attractive substance. During heavy rains, more or less water entered through these holes, and this necessitated a change of method. After this experience a 3-ounce uncovered can filled with cotton (fig. 3) was used. The extract was poured on the cotton and the can then inverted and fastened to the tree in this position. The inverted open can protected the extract from rains, and allowed the odors to escape more evenly. A sticky substance applied to the tree trunk around the trap served to catch the males coming to and hovering about the trap.

The cages or traps were usually placed near the roadside in the edges of woodland, neglected orchards, or sprout growth, and along the edges of fields, because such localities were more apt to be infested and could also be more easily visited. The cage was fastened on the side of a tree away from the road so as not to attract attention. During seasons when a large number of cages were put out they were placed along roadsides three-fourths mile or 1 mile apart, and in special experiments and locations as near together as one-fourth to one-half mile.

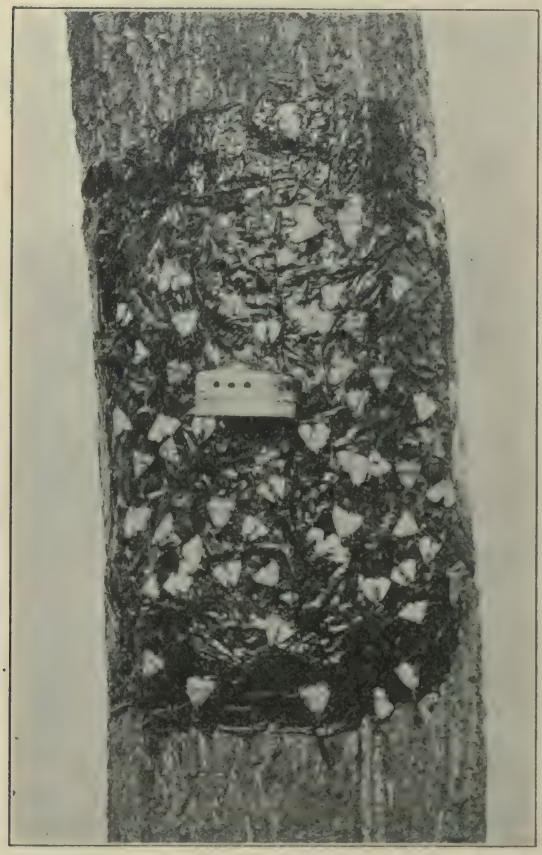


FIGURE 2.—A covered tin salve box as used in early experiments with extracts. A single day's catch of males is shown in the sticky material

In obtaining data on distances or direction males were attracted (or flew to find females) it was necessary to mark and liberate many males, and distinctive markings were necessary to indicate the various liberation points. Aniline dyes mixed with 70 per cent alcohol were used in 1913 for this purpose. The different colors were applied to certain wings by means of a small camel's-hair brush. The males flutter about considerably in the boxes, and marks made with the above mixture would sometimes spread to other wings than those marked or to parts of the body before drying, making its use unsatisfactory. Artists' oil paints thinned with gasoline were later used in the same manner and with much better results. The colors did not spread so rapidly and dried much more quickly.

In 1928 male pupae were put in a darkened box with a cone at one end, through which the males, soon after issuing, crawled toward the light. A wick extending from a bottle of dye solution was held in the cone, and as the males crawled over the wick in order to get through the cone they became marked with the dye. When they were caught at the trap a solvent was used to dissolve the sticky substance and dye in order to determine the source of the moths. The marked males were liberated at various points from one-sixteenth mile to 1 mile dis-

tant from the central female cage, and notes were taken on the time of flight and direction and distance from which they were attracted to the trap.

LIVING FEMALE MOTHS AS SOURCE OF ATTRACTION

During July and August, 1913, some preliminary experiments were conducted near the western border of the New England area then known to be infested.[5] The purpose of these experiments was

FIGURE 3.—An open can filled with cotton into which an attractive solution has been poured: A, In position for receiving the attractant; B, inverted. Adhering to the sticky material is shown a day's catch of males.

to obtain data on the number of males that might be attracted to a given point, the idea being to follow up the catches by scouting to determine the distance to the nearest infestation and the direction from which the males came. Ten cages were put out in as many locations, each location being a few miles from any known infestation. Twenty female pupae, from which 10 to 13 female moths issued, were inclosed in each cage. From 1 to 6 males were caught at six of the

[5] In 1913 this area in Massachusetts extended from the northeast corner of Connecticut in a zigzag line to Northfield, Mass., where the Connecticut River enters Massachusetts, thence northeasterly in New Hampshire to Ellsworth and Thornton in Grafton County, thence eastward into Maine.

cages. Detailed scouting was later done around two of these six cage sites to a distance of one-half mile and 2 miles, respectively, but no infestations were found.

Some similar experiments were conducted in 1914. Ninety-three cages were distributed in 23 towns of Maine, New Hampshire, and Massachusetts about the middle of July and removed the middle of August. One or two males were caught at 25 of these cages. Some intensive scouting was done the following fall in a few selected locations to determine the nearest infestations. A rather interesting find was made in Rumney, N. H., consisting of four infestations, located as follows with reference to cages: One infertile egg cluster two-thirds of a mile south of a cage which attracted 2 males; one fertile egg cluster 1½ miles east of a cage which attracted 1 male; another fertile egg cluster two-thirds of a mile southeast as well as a trace of an egg cluster 1⅓ miles southwest of a cage which attracted 2 males. The first two infestations were found by the regular scouting crews examining favorable tree growth along roadsides, edges of woodlands, and all scattered trees in the open, and the last two by a special scouting crew that carefully examined the whole of the wooded area.

One infestation in Westmoreland, N. H., was 1⅛ miles from a cage that attracted males, but the infestation was not located until the second year of scouting after the catch was made. Other interesting catches of males were made in Stoddard and in Gilsum, N. H., in 1914, and near-by infestations were found during the scouting seasons of 1914–15 and 1915–16. Infestations were located in one of those years within 500 yards, one-half mile, and 1 mile of the attracting cages.

Three males were attracted to a cage near the town line of Newport and Croyden, N. H., in 1913. Subsequent scouting did not reveal any infestations that season. Another cage was placed in the same location in 1914 and a circle of cages around it as a center, ranging from three-fourths mile to 1½ miles distant. Owing to exceedingly poor issuance of females from the pupae, poor results were secured. One cage, however, attracted 1 male, and subsequently one fertile egg cluster was found one-fourth mile south. To show that the attraction of 3 males to the first cage in 1913 was indicative of general conditions, an infestation of 66 fertile egg clusters was found about 2 miles east during the 1914–15 scouting, and two egg clusters at one-half and three-fourths mile distant. Several additional egg clusters were found distributed over an area within 1½ miles of the 1913 cage site.[6]

FLIGHT OF MALES AND PROPORTION FINDING FEMALES

Tests to obtain data on the flight of males and the proportion finding females from given distances were conducted at North Dartmouth, Mass., in August, 1913. In these tests fresh males were marked with aniline dyes in 70 per cent alcohol. The marking was done in the early forenoon, when the males were least active, with different colors on the right or left fore wing to denote liberation

[6] Though no intensive scouting was done around cages which did not attract males it is probable that some infestations existed within the same distances from those not attracting as from those that did. Later experiments have shown that these variable results may arise from such conditions as unfavorable topography, wind, temperature, or dense tree growth.

point. In all, 275 males were liberated three-fourths mile and 1 mile in different directions from a central cage containing 35 virgin females.

One unmarked male was taken at the central cage, and after scouting a small natural infestation was found one-fourth mile east from which it may have come. Two days later a marked male from the liberation three-fourths mile north was taken. The counter attraction offered by such natural infestations may account for the fact that no other of the marked males were caught.

On July 9, 1914, a cage containing 20 female gipsy-moth pupae was attached to a post on Lunging Island, Isles of Shoals, off the coast of New Hampshire. This island, which is small and rocky, was not infested, the nearest infestations being on White Island, one-half mile distant; Appledore Island, five-eighths mile distant; and Smutty Nose Island, three-fourths mile distant. On August 8, 33 other females were added to the cage. On August 31 the cage was examined, and 79 males had been caught. It was interesting that all the males were caught on the side of the trap toward the infested islands.

A similar test was conducted at Race Point, Provincetown, Mass., August 9 to 25, 1915. A cage containing 20 females was attached to a telephone pole on the beach near the lighthouse. The nearest infestations were in woodlands beyond some sand dunes from 1¼ to 1½ miles to the east and southeast and from 1¾ to 2 miles to the northeast. Nine males were caught this year, and in a repetition of this experiment in August, 1917, 59 males were caught.

Experiments to obtain more data were conducted on Lynn Marshes near Lynn, Mass., in 1915. This is a broad expanse of treeless, salt marshland relatively free from gipsy-moth infestation. Six experiments were conducted from August 10 to 15 by liberating marked males with, against, and at right angles to the winds at distances from 150 yards to three-fourths mile. Results from liberations at 150 yards and one-fourth mile distant showed that the males fly against the wind in almost all cases. Of 362 marked males, 27, or one-thirteenth of the number liberated, were caught. Ninety-nine unmarked males, however, came to cages from near-by infestations 150 yards to 1 mile distant. Four of 18 marked males liberated one-fourth mile to the northwest were recovered between 45 minutes and 3 hours and 40 minutes after liberation. The marked males all came flying against the wind.

Other experiments were also conducted on marshlands at the same time by liberating 72 marked males about noon leeward of the wind, and three-fourths mile distant from a cage of 40 virgin females. The cage was watched during the most active flying period. Seven males were caught in 24 hours. One was marked, and six were unmarked. All had flown at least three-fourths mile. It was noted that other males came to the cage from a direction against the wind but were not caught.

On August 13, 50 marked males were liberated at two points three-fourths mile to the southeast of the cage. The liberations were against the wind, as in the above experiment. The wind, however, soon shifted from northwest to westerly and southwesterly directions. No marked males were attracted, presumably owing to the

shifting of the wind. Five unmarked males were caught in less than two hours. No marked males were caught in any of these experiments over four days after liberation. The nearest infestation was one-fourth to one-third mile distant.

On August 14 and 15, at 11.30 a. m., 75 marked males were liberated each day at three points three-fourths mile in an east-northeast to east-southeast direction from the cage. The wind was blowing from the west with a velocity of from 7 to 8 miles per hour. The temperature was 89° F. in the sun. A total of 33 males were caught, 6 of which were marked and had come against the wind. Two of them had been liberated at the ¾-mile liberation point August 11. The other four flew three-fourths mile against the wind and were caught after intervals varying from 55 minutes to 1 hour and 45 minutes from the time of liberation. Many were seen coming to the cage in general progress, but in a zigzag manner of flight, and were observed over a distance of 200 feet or more before reaching the female cage.

A series of liberations were made at Amherst, Mass., between July 25 and August 9, 1918, and repeated in July, 1919. In 1918 two cages, each containing 15 virgin females, were located on the campus of the Massachusetts Agricultural College, one 12 feet from the ground and the other 70 feet high on a building. It was hoped to compare the catch at the two heights and to learn whether males follow the scent directly or fly quite close to the ground regardless of the exact situation of the females.

A total of 914 males were liberated in 1918. No recoveries were made 70 feet above the ground, but three marked males were taken at the lower cage two days after being liberated, having come against the wind, apparently following the scent.

In the experiment in 1919 only the cage 12 feet from the ground was used. Marked males were liberated from the four cardinal directions, and out of 1,873 only 5 were recovered.

The direction of the wind during the interval between liberation and recovery indicated that the males sometimes came at right angles to the direction of the wind, or with it, as well as against it. The records also indicated from the small number of males recovered that they are ordinarily not attracted to females from distances of more than one-fourth or one-half mile. The distance they are actually attracted may be even less, as they apparently fly aimlessly for a considerable distance, finally locating the females by scent from shorter distances.

DISTANCES MALES FLY IN SEEKING FEMALES

When this method of attracting males is employed to locate infestations, it is important to know the maximum distances from which the males may come. To secure data on this phase of the problem some uninfested localities were selected on barren lands and rocky islands along the coast of Massachusetts and Maine, within a few miles of areas known to be infested. On selected sites cages were put out containing from 40 to 50 female gipsy-moth pupae from which 12 to 15 females issued. Fifteen treeless islands in Casco Bay and one off the coast of York, Me., were used for these

experiments between August 3 and 25, 1915. These islands were situated at distances ranging from five-eighths mile to 7 miles from infestations with only the ocean between them. The catches of males ranged from 0 to 13 at each cage. Some scouting was done in the fall to determine the nearest known infestation on other islands. All the cages attracted males excepting two that were molested and one at Boon Island located 7 miles from the infested mainland. The largest catch consisted of 13 males, made on Upper Flag Island located five-eighths mile from an infestation on Haskel Island. Another catch of eight males was made on Little Bang Island. The nearest known infested island was Great Chebeague, five-eighths mile to the northwest. Another interesting catch consisted of four males on Sturtevant Island three-fourths mile northwest from the mainland, and the same distance from Basket Island to the south-southeast. The most significant catch was one of two males on Outer Green Island, located $2\frac{1}{2}$ miles from Jewell Island and $2\frac{3}{8}$ miles from Cliff Island, both to the northeast, and Peak's Island $2\frac{3}{4}$ miles to the northwest.

In 1917 some experiments on islands distant from infestations, and two additional experiments on the mainland, were repeated as checks. Two males were again caught on Outer Green Island and none at Boon Island as in 1915. Four males were caught on Billingsgate Island off Cape Cod, Mass., and scouting indicated that the nearest infestation was $2\frac{5}{16}$ miles north on the mainland. The males, in reaching this cage, were not obliged to fly more than a mile across water without resting, for a sandy point extends southward as part of the mainland.

These experiments indicated that small numbers of males can and do fly as far as $2\frac{5}{16}$ miles, but do not, under similar conditions, fly as far as $3\frac{1}{4}$ miles. Local conditions, such as those met with in these experiments, may increase the distance from a given point at which males may be recovered.

DISTANCES MALES FLY IN CONFINEMENT

In order to check the field experiments on distances males fly in seeking females, a few laboratory experiments were conducted in August, 1917. These were carried on in a room 12 by 14 feet, at a temperature of about 80° F., with curtains drawn to subdue the light. Preliminary tests indicated that males flew an average distance of 150 feet per minute where no air currents assisted or deterred their flight. Records were kept of the duration of flight and the number of times the males flew around or across the room, and distance computations were made from these. Males were used before and after mating. They are diurnal and were confined in large pill boxes at night.

Eleven males, 24 hours old, which had not mated, were tested first. One flew continuously for 1 hour and 2 minutes, and during another period 4 minutes. It covered a distance of 9,900 feet or 1.87 miles, and died the third day. The average flight for these 11 males was 0.62 mile. They all lived three days.

Ten males that were 48 or more hours old were allowed to mate. Two of these refused to fly, and two others flew only four and five minutes, respectively. The average flight of the eight males which

flew was 0.66 mile. One of this lot flew continuously for 1 hour and 11 minutes, and the following day 13 minutes, covering 12,600 feet, or 2.38 miles. It flew 2 miles without resting. Specimens of this lot died the second, third, and fourth day after mating. Confinement in pill boxes undoubtedly hastened death. The indication that mated males fly slightly farther than unmated males may possibly be due to the small number of instances recorded.

It is interesting that the maximum distance covered by a male in confinement, namely, 2.38 miles, was very similar to the records secured on the treeless islands in Casco Bay near Portland, Me., and at Billingsgate Island, Mass.

TESTS OF TRAPPING MALES ON A LARGE SCALE

Since several striking catches of males had been made in border territory infested by the gipsy moth where it was not always possible to find an infestation within 1 or 1½ miles of the cage site, it was decided in 1917 to put out a large number of cages in border territory infested by the gipsy moth which would be subsequently scouted. Accordingly, 62 towns were selected adjacent to, but just inside, the 1917 quarantine line. This tier or strip of towns (double, or two towns wide, over much of the area traversed) extended from Long Island Sound, at the southeastern corner of Connecticut, to Southbridge and Monson, Mass., thence to Hinsdale, N. H., from which point it followed the Connecticut River Valley northward to Piermont, thence across to Chatham, N. H., which borders on the State of Maine. In the outer tier of towns the cages were three-fourths mile apart; in the inner tier they were placed 1 mile apart. An additional town, however, was selected where cages were placed 2 miles apart. A total of 2,743 cages were put out that year in the 62 towns, along 4,169 miles of road. There were from 19 to 177 cages per town, the number varying according to the size of the town [7] and the number of miles of road it contained. The cages were attached to the side of a tree away from the road (usually within 50 to 100 feet of it) and a "Do Not Molest" notice was attached to each cage. Fifteen carefully selected female pupae were placed in each double-walled cage, and a tin disk was tacked over the hole and sealed with sealing wax so that it would be known if any cages were molested. The average number of females emerging from the 15 pupae in the cages in three towns in Connecticut was 11.5, while the general average for the whole was somewhat less.

In 58 of the 2,743 cages put out that year no females issued, leaving a total of 2,685 cages charged with females. To these a total of 17,733 males were attracted, or an average of 6.6 males per cage. Many of the cages did not attract any males and many others only 1 or 2, while the maximum number caught at any one cage was 95. Not many more than this number would adhere ordinarily to the sticky surface of from 100 to 144 square inches, as the material is rendered ineffective by the scales from the wings and by the dead bodies of the males.

Table 1 shows that there were proportionately about as many males caught at cages placed 1 mile apart as at those three-fourths

[7] The area of towns in New England varies. The average size of the towns included in this experiment was approximately 38 square miles.

mile apart. This is because the inner tier of towns, where cages were placed 1 mile apart, was more heavily infested than the outer tier of towns, where cages were nearer together. It is thought that cages placed three-fourths mile apart gave results more indicative of the actual number of infestations in the towns.

TABLE 1.—*Average road miles and acres represented per male caught, 1917*

Distance between cages on road	Towns	Cages	Total road miles	Area [1]	Total males caught	Miles per male caught	Area per male caught [1]
	Number	*Number*	*Number*	*Acres*	*Number*		*Acres*
¾ mile	37	1,941	2,506.4	819,724	10,826	0.2315	77.55
1 mile	25	802	1,663.2	512,662	6,907	.2408	76.12
Total	62	2,743	4,169.6	1,332,386	17,733		

[1] The total area, and area per male caught, included in the table are based on the record for only 54 of the 62 towns (31 towns with cages three-fourths mile apart and 23 towns with cages 1 mile apart), as the exact acreage of 8 Connecticut towns is not known.

During the following fall and winter regular roadside scouting was done in many of the towns where cages attracted males, and data were compiled on the number and degree of the infestations found. In some cases it was impossible to determine whether the small number of males attracted to a given cage was due to the emergence of the females in the cage being much earlier or later than that of the males in the open infestation, or whether the attraction in the natural colony was great enough to prevent the males leaving their own locality. It is probable that the former is true, since in most cases where a fresh supply of females was introduced into cages near infestations the recovery was larger. After some scouting was done in the towns, records were compiled which indicated that catches at the cages in general compared with the number of egg clusters found at the nearest infestations. In New Hampshire and Vermont these infestations were found at an average of 1,813 feet (about one-third mile) from the cage, and those in Massachusetts and Connecticut 1,361 feet (about one-fourth mile) from the cage. These records further indicated that the males originated in the vicinity of the cage at which they were caught and did not fly long distances. Intensive scouting in the vicinity of some cages disclosed a few infestations not located by the scouts in their regular roadside work. It should be stated also that there were instances where infestations were found within a few hundred feet of cages that did not attract males. The records showed that the towns near the border were more heavily infested than previous scouting operations had indicated.

Some follow-up experiments were conducted in July, 1918, in 11 selected towns where fairly large catches of males were made in 1917. The catch was small in 1918. There were no males recovered at many cages, probably because of the extremely cold winter of 1917–18, which killed many gipsy-moth eggs and probably exterminated many isolated colonies. Some of the cages attracted from 1 to 12 males each in 1918, and during the spring of 1919 intensive scouting was done in a few selected localities where catches of 2 or more males had been obtained. Two reinfestations were discovered

in Scotland, and one in Lisbon, Conn., towns which apparently had no infestations the preceding winter. Two new infestations and one reinfestation were found in Hardwick, Mass. All these infestations were less than one-eighth mile from points where cages that attracted males were located.

Similar results were obtained in 1919. Intensive scouting in December, 1919, revealed infestations 200 yards, and one-eighth, three-eighths, and one-half mile distant from cages that attracted males. In other instances old hatched egg clusters were found within a few hundred yards of cages that attracted males.

RECOVERY EXPERIMENTS WITH EXTRACTS IN MAINE

In 1928 an experiment was conducted in a very lightly or non-infested district at Dover-Foxcroft, near the center of the State of Maine, with the object of determining what percentage of males liberated in a given locality could be recovered by traps containing extracts of female abdominal tips (fig. 3) at various distances from the point of liberation. In addition, some information was desired on the influence of temperature, rain, humidity, topography, and forestation.

In natural infestations there is generally some counterattraction resulting from the scent of living females in the colony. Therefore, to approximate natural conditions, from three to five living unfertilized females were kept in cages from 3 to 10 feet from the points of liberation. Some males flew around and against these cages for a few minutes and soon left, while others would alight on a cage, remain for a while, and then fly away. Though the female seldom mates more than once, the males may mate from one to five times, if enough females are available. It also appears that more males normally emerge in a given infestation than females, owing to the fact that the shorter larval stage of the former insures a better chance for survival.

Two liberation experiments were made with 590 and 811 individuals, respectively. In each case an equal number of male pupae were put in rain-proof boxes attached to trees about 5 feet above the ground and so arranged that when the males issued they could fly away normally. The boxes were distributed at regular distances around a central extract trap. For the first experiment thirty 1-year-old tips in benzene were used for the attractant, and the liberations made at distances of ¼, ½, and 1 mile; and for the second experiment 15 tips of fresh material in xylene were used, and males were liberated at distances of $\frac{1}{16}$, ⅛, and ¼ mile from the central trap. These distances are equivalent to the theoretical maximum distances of traps from road infestations along a straight road when traps are spaced twice these distances, for example, ⅛, ¼, ½, 1, and 2 miles apart. In the case of traps one-half mile apart, therefore, the greatest distance from an infestation along the road to the nearest trap will be one-quarter mile, and the average distance will be one-half this, or one-eighth mile. No marked males were caught at traps 1 mile and one-half mile from points of liberation, but 11, 17, and 69 males were caught at distances of ¼, ⅛, and $\frac{1}{16}$ mile, respectively.

Upon the theoretical assumption that attraction varies inversely with the square of the distance—and if also it is limited to a distance of, say, one-fourth mile—then if a series of traps were distributed at half-mile intervals along a straight road, attraction would diminish to zero half way between the traps and in a circle one-fourth mile from each trap as a center.

The percentage of males that can be recovered by extracts is dependent on a number of variable factors, the more important of which are the distance they can fly, vitality and length of life, distance from the trap, number of males, wind direction and velocity, rain, humidity, temperature, counterattraction by females of a colony, tree growth, topography, and the attracting power of the extract. Considerable variation should be expected, therefore, in the results of the experiments.

The extracts were measured out at the laboratory at Melrose Highlands, Mass., and poured in 1-ounce vials stoppered with cork, and taken by automobile to Dover-Foxcroft. Unfortunately considerable of the attractive substance used in all the 1928 recovery experiments was lost by this method of handling, as is shown by the following comparative test: The contents of three vials brought back from Maine were put out at Saugus, Mass., on August 2, and the effectiveness of this material compared with that of six other traps containing xylene extract that had been taken direct from the Melrose Highlands laboratory to Saugus. The three traps containing unused material brought from the Maine recovery experiments caught an average of 22.3 moths, while the six traps of fresh laboratory material caught an average of 64.7 moths.

The low summer temperature in the locality where the Maine experiments were conducted was one of the main causes for the low recovery at the traps. Observations, both at the laboratory and in the field, showed that the males would never fly voluntarily when the temperature was below 70° F., and that their activity increased as the temperature rose from 70° to 90°. One observation was made at 95°, when activity was at least as great as at 90°. The number of males caught varied with the number of available hours [8] and with the number of degrees of cumulative excess temperature [9] above 69°. (Table 2.) The distance males can fly to extract traps depends considerably on the temperature. At Dover-Foxcroft, Me., there were only 60 per cent as many hours when the temperature was above 69° as at Melrose Highlands, Mass., and only 33 per cent as much cumulative temperature above 69°. Rain or wet foliage stopped the flight of males, but they appeared to be attracted somewhat better when the heat was accompanied by humidity, provided the foliage was dry.

---

[8] An available hour for flight of males is an hour during which the temperature is above 69° F.

[9] A degree of cumulative excess temperature is counted by each degree of temperature above 69° F. during an hour. A temperature of 73° F. for one hour would make 73—69 or 4 degrees of cumulative excess temperature. The same for three hours would give 12 degrees of cumulative excess temperature, etc.

TABLE 2.—*Effect of certain weather conditions on recovery of males of the gipsy moth, 1928*

Date of liberation	Dover-Foxcroft, Me.				Melrose Highlands, Mass.	
	Hours above 69° F.	Cumulative temperature	Males caught	Character of day	Hours above 69° F.	Cumulative temperature
	Number	*°F.*	*Number*		*Number*	*°F.*
FIRST LIBERATION—FIRST SERIES OF EXPERIMENTS						
July 20	0	0	0	Clear	0	0
July 21	10	39	2	Clear, calm	9	29
July 22	6	10	0	Cloudy	0	0
July 23	0	0	0	Rain	2	2
July 24	8	19	2	Clear	7	18
July 25	12	60	2	Clear, warm	10	111
July 26	6	8	1	Clear, calm	4	4
July 27	0	0	0	Cloudy, rain	8	16
July 28	0	0	0	Heavy rain	7	18
July 29	0	0	0	Clear	9	9
July 30	0	0	0	do	7	13
July 31	7	14	0	do	8	41
Total	49	150	7		71	261
SECOND LIBERATION—SECOND SERIES OF EXPERIMENTS						
August 1	10	52	21	Partly cloudy, warm	10	40
August 2	8	36	25	do	12	148
August 3	5	4	12	Partly cloudy to showers	14	184
August 4	9	52	24	Clear to partly cloudy	14	196
August 5	0	0	0	Cloudy	12	52
August 6	0	0	0	do	0	9
August 7	3	8	6	do	0	0
August 8	0	0	0	Rain	0	0
August 9	0	0	0	do	6	80
August 10	1	1	1	Cloudy	1	18
August 11	1	1	1	Clear	4	1
August 12	0	0	0	do	0	1
Total	37	154	90		73	666
Total for both liberations	86	304	97		144	927

When liberated in an open field the males showed a very noticeable tendency to seek the edges of woods and roadsides, many entering the woods after flying back and forth along the edge. It was also noticed that males in the woods very seldom come out into open fields unless attracted outside by the scent of females. Whether this tendency to fly in the vicinity of tree growth is instinctive, or arises from the use of sight, or from the detection of forest odors is a question.

Where there are hills between the point of liberation and the trap, not so many males are caught as where the males have unobstructed fields to fly across.

CHEMICAL STUDIES OF THE ATTRACTING SUBSTANCE

Early experiments indicated that the males were attracted by an odor given off by the females. It was hoped that it would be possible to determine whether a definite substance of attractive power was present in the females, and if so to isolate it, determine its

nature, and, if possible, prepare it in quantity synthetically for use in trapping the moths. Accordingly, A. F. Burgess and the senior author approached W. R. Bloor, of the Harvard Medical School, and engaged him temporarily to assist in making these studies, Doctor Bloor's report [10] is in part as follows:

In a large cage out of doors, gipsy moth males were strongly attracted, not only to living females but also to the whole or parts of the abdomen of females. When males had begun to fly in considerable numbers in Sharon, Mass., most of the succeeding experiments were conducted at that place. Later, when moths were present in considerable numbers at the Medical School in Boston, experiments were conducted there.

The work was made quantitative by use of the "Shaw" trap [11] covered with a sticky mixture. The trapping tests were carried out along two lines; (1) with various extracts of the female moth, and (2) with chemical substances, and later with natural products, e. g., resins. As regards the second type of substances (chemicals, etc.), many were tried, and the following attracted moths in the order named: Allylamine, ethylamine, and methylamine. Slightly active were quinoline, which attracted very many, but caught few (three in one-half hour), and benzonitril which caught several flies but only one moth. A peculiarity of all of these substances was that they attracted when first put out but were not sufficiently attractive to catch a large number of moths, and lost their power in the course of an hour or so, pointing to the probability that there were present traces of an actively attracting substance which was soon lost by volatilization.

Results from extracts made from the bodies of female moths may be summed up as follows: (1) Water extracts contained only traces of the active substance, and this could be extracted from the water by shaking with ether. (2) Ninety-five per cent alcohol extracted all the active substance. (3) The active substance was readily soluble in ether and less readily soluble in petroleum ether (naphtha). (4) These solubilities indicated that the substance was probably a lipoid (fat or related substance). A sample was saponified with sodium ethylate and a separation made of saponifiable (fatty acids) from unsaponifiable substances. In this "unsaponifiable" group would be included various substances belonging to the aromatic group, as cholesterol, resins, terpene derivatives, etc. Both saponifiable and unsaponifiable parts were tested for their power of attraction, and the active principle was found to be present almost entirely in the unsaponifiable portion. Attempts to divide this portion by fractional distillation at low pressure with temperatures up to 100° C. and with the receiving bulb in a freezing mixture were not successful. The crude petroleum ether extracts were fractioned as regards their solubility, and the active substance was found to be in the most soluble fraction. (5) Extracts made from various portions of the body of the female showed that the attractive substance was present in quantity only toward the last segment of the abdomen; and, therefore, probably had its origin in the accessory sexual glands of the oviduct. (6) The active substance seemed to be quite stable. The first alcoholic extract of abdomen, free from eggs and hair, remained active 22 days when exposed in the field. When freed from its fatty impurities it was active for a shorter time, owing possibly to its volatilization not being impeded by these fatty substances. (7) The males seemed much more sensitive to attraction in the fore part of the season than in the latter part. They would at first be attracted to extracts containing probably traces of the active substance, which later in the season had no effect on them.

The results thus far obtained appear to justify the following conclusions: (1) That the males are attracted to the females by the odor of a substance produced by the females, probably in glands toward the last segment of the abdomen, and (2) the substance is relatively stable, is soluble in alcohol and in the ordinary "fat solvents," and slightly in water. After saponification the active material appears in the unsaponifiable fraction.

---

[10] Unpublished.

[11] The Shaw trap has four vertical wings like a 4-bladed paddle wheel set on end, with a small cage for the females set into an opening made where the blades intersect at the bottom. These blades are covered with a sticky mixture which catches and holds the insects. The insects coming from any certain source are naturally caught in the angle opening in that direction.

The next season C. H. Fiske, biological chemist at the Harvard Medical School, was temporarily engaged. A part of his report [12] is as follows:

Proceeding on the assumption that the active material is volatile, an examination of distillates from alcoholic extracts of female abdominal tips was made along various lines.

Analysis of one such extract (1,500 abdominal tips) showed it to contain 35 milligrams of nitrogen. A portion of the same extract, distilled from alkaline solution, gave an amount of volatile base (in the distillate) equivalent to 33 milligrams of nitrogen. This distillate, acidified with hydrochloric acid and evaporated to dryness, left a small residue consisting, as far as could be determined, entirely of ammonium chloride. Practically all the nitrogen in the original extract was, therefore, recovered as ammonia, leaving no possibility of the presence of other volatile nitrogenous bases in more than the minutest traces. The chances of the active substance being of this nature is consequently very slight.

In the course of the above procedure, it was found that the distillate gave a bulky yellow precipitate (mercury compound) with Nessler's reagent (an alkaline solution of mercuric potassium iodide). The same yellow substance was obtained in purer condition (since uncontaminated with ammonia) after distillation of the alcoholic extract with acid instead of alkali. It contains 66 per cent of mercury and gives qualitative tests for iodine, but is free from nitrogen, sulphur, and phosphorus. After removing the mercury from the precipitate, and distilling again, this time from alkaline solution, there is still about the same quantity of substance concerned to be found in the distillate, showing (1) that it can be recovered from the mercury compound, and (2) that it is not an acid.

Similar precipitates were obtained from other mercury reagents (reddish precipitate with mercuric chloride; white precipitate with an alkaline solution of mercuric cyanide). These tests suggest the presence of an aldehyde or a ketone, and it was accordingly found that the distillates gave a strongly positive test for aldehyde with Schiff's fuchsin reagent (red color). Analysis of the above distillate by Ripper's method showed the presence of 0.03 per cent aldehyde (calculated as acetaldehyde). By the same method, the distillate from another extract containing a larger number of tips showed 0.06 per cent aldehyde.

Attention was then directed toward the characterization of the aldehyde. The most suitable reagents for this purpose were not available at the time, so as much information as possible was sought with reagents that were in stock or that could be prepared readily. After various unsuccessful preliminary tests with other reagents, thiosemicarbazide was finally selected as suitable for more detailed investigation, since both it and its aldehyde derivatives are readily analyzed, particularly in the form of their silver compounds. Nevertheless, in spite of numerous attempts to isolate a compound of this reagent with the aldehyde present in the distillates, nothing has so far been recovered but a substance which, as shown by its physical properties and by the silver content of its silver compounds, is merely unchanged thiosemicarbazide. The desired condensation product, therefore, either is not readily synthesized under the conditions adopted, or is too unstable to resist the manipulations that would be necessary to isolate it.

The most promising direction for further work would be an attempt to apply, in a similar way, other reagents not now obtainable on the market, particularly p-nitrophenyl-hydrazine.

When the services of Doctors Bloor and Fiske were no longer available, B. L. Souther, organic chemist working at Harvard University, was temporarily engaged to assist in making the chemical investigations. E. P. Kohler, head of the department of organic chemistry at Harvard, directed the work of Doctor Souther and offered many suggestions for trial and improvement. A summary of Doctor Souther's report [12] is as follows:

---

[12] Unpublished.

Experiments were first made with old material held over winter in cold storage (0° to 3° C.) and later checked with fresh material with the object of determining (1) the general class, or classes, of organic compounds to which the attractive substance belongs, (2) the procedure that would give the most complete extraction of the material from the abdominal tips, and (3) a possible method of isolating the substance. The samples were put out in tin evaporating boxes and attached to trees.

Thirty-two samples of filtered extract, each from a minimum of 250 abdominal tips in 21 c c of petroleum ether, were treated with various reagents and then subjected to field tests, with the results recorded in Table 3. Four untreated samples of the same concentration were used as checks. All of the samples were prepared from female tips. The more important experimental procedure is described below.

TABLE 3.—*Tests with samples of the solution of abdominal tips of female gipsy moths, showing numbers of male moths attracted to traps after various treatments of the solution, Saugus, Mass., 1921*

Sample No.	Treatment of sample [1]	Female tips used	Total males caught	Sample No.	Treatment of sample [1]	Female tips used	Total males caught
		Number	*Number*			*Number*	*Number*
1	Check solution [2]	250	95	17	Distillate evaporated on filter paper	250	3
2	Treated with sodium carbonate to remove acids	250	374	18	Test for base as in sample 3	500	13
3	Treated with sulphuric acid to remove bases	250	117	19	Hydrolysis of extract with potash	250	15
4	Treated for unsaturated compounds	250	13	20	Test for unsaturated compounds	250	183
5	Test for aldehyde	1,000	119	21	Test for aldehyde	250	182
6	Oxidation of dried tips	1,000	7	22	Boiled with potash	250	80
7	Hydrolysis of dried tips	1,000	119	23	Most volatile of two portions	250	8
8	Most volatile third of three lots	250	217	24	Second portion of distillate	250	75
9	Second portion of three lots	250	73	25	Solvent added and distilled off	250	41
10	Third portion of three lots	250	16	26	Distilled at 150° C	250	207
11	Residue distilled at 100° C	250	1	27	Solvent added and distilled off	250	23
12	Residue distilled at 125° C	250	0	28	Residue	250	8
13	Residue distilled at 150° C	250	314	29	Check solution [2]	250	214
14	Final residue	250	36	30,31, 32,33	See text	[3] 250	1
15	Check solution [2]	250	118	34	Hydrolysis of extract with sodium carbonate	250	42
16	Nonvolatile portion of one lot	250	15	35	Check solution [2]	250	8
				36	See text	250	0

[1] Refer to text for more detailed information on the composition and treatment of each sample.
[2] Check sample 1 covers samples 1 to 14, check sample 15 covers samples 15 to 28, check sample 29 covers samples 29 to 34, and check sample 35 covers sample 36.
[3] 250 used in each sample.

TEST FOR ACID

An old lot was extracted twice with 5 per cent sodium carbonate solution, washed with water, and dried. (Sample 2.) This sample attracted more moths than the check solution, proving a previous conclusion that the substance is not an acid. A new lot was also hydrolyzed with sodium carbonate and caught 42 moths. (Sample 34.)

The greater attractiveness or activity of sample 2 as compared with the check solution indicates that the active material is continuously being generated by hydrolysis from a more complex compound.

A sample of fresh material was hydrolyzed with the more active potassium hydroxide, instead of sodium carbonate, and the extract was not very active, indicating that it was not stable in strong, cold alkalies. (Sample 19.)

HYDROLYSIS WITH ACID

One thousand tips which had been covered all winter with petroleum ether were decanted and washed with petroleum ether and dried in the open air. As soon as the tips became dry they were moistened with 1 per cent hydrochloric acid and shaken overnight. The acid was neutralized with sodium carbonate, and the resulting solution extracted with ether. (Sample 7.) It caught many moths, thus confirming the hypothesis that hydrolysis plays an important rôle in causing extracts to retain their activity, the moisture of the air acting as the hydrolyzing agent in the field experiments. Oxidation is not concerned in the process, as shown by the results with 1,000 tips which had been decanted, washed with ether, and dried, as in sample 7. These were moistened with water and shaken with oxygen under 13 pounds pressure, the material extracted with ether, and the solution dried, but when tested it caught only seven moths. (Sample 6.)

TEST FOR BASE

A sample was extracted twice with 5 per cent sulphuric acid, washed with water, and dried. It caught many moths; this shows that the attractive material is not a base. (Sample 3.) Six per cent hydrochloric acid was next used instead of sulphuric acid, but this sample was only slightly active. (Sample 18.)

TEST FOR UNSATURATED COMPOUNDS

Potassium permanganate in neutral solution readily oxidizes many unsaturated compounds. Therefore, two samples were shaken overnight, each with 25 c c of a 3 per cent solution of potassium permanganate. (Samples 4 and 19.) The results showed conclusively that the attractive principle is a saturated compound and is not unsaturated.

TEST FOR ALDEHYDES

A portion of extract was boiled for two hours with hydroxylamine and potassium hydroxide. The alcoholic solution was evaporated and the residue poured into water and extracted with ether after acidification with weak hydrochloric acid. This procedure would remove all aldehydes and all but complex ketones. The extract attracted many moths; this shows that the active principle is not an aldehyde. (Sample 5.) The test was repeated, and at the same time another extract sample was boiled with potassium hydroxide in order to determine whether the alkali or the hydroxylamine caused the change, should any be observed in the solution. Both samples were active. (Samples 21 and 22.)

VOLATILITY TESTS

It was also desirable to determine, if possible, the volatility of the attractive constituent. Accordingly, a quantity of the solution equivalent to three lots (63 c c) was fractionally distilled from a steam bath. The first 21 c c that distilled was very attractive and caught 217 moths. (Sample 8.) The second fraction that came

over was less attractive and caught 73 moths. (Sample 9.) The third distillate consisted of the last portion that would not distill at steam-bath temperature, and was even less attractive, catching only 16 moths. (Sample 10.) The residue was heated for an hour at 100° C. in a current of air under diminished pressure, but the distillate was not active. (Sample 11.) The heating was continued at 125° for an hour; yet no active material distilled. (Sample 12.) After an hour's heating at 150° a small amount of distillate collected, and this sample was very active. (Sample 13.) The discolored residue that remained in the flask was washed out with solvent and tested, but it caught very few moths. (Sample 14.)

A lot was evaporated in a vacuum at room temperature, the distillate being collected in a flask immersed in a freezing mixture. The portion that would not distill caught very few moths. (Sample 16.) To present as large a surface as possible for evaporation, pieces of filter paper were put in the flask containing the condensate. The liquid was then evaporated under diminished pressure. The paper and the small amount of liquid which remained in the flask caught very few moths. (Sample 17.) That few moths were caught from these two tests (samples 16 and 17) is very strange, but local field conditions may have been responsible for the result.

Another series of volatility tests were carried out using a double portion of the extract. The most volatile portion was only slightly active (sample 23), but the second portion of the distillate showed considerable activity. (Sample 24.) In order to remove, if possible, all of the active compound, petroleum ether was added to the residue and distilled off immediately. This solution caught many moths, but quickly lost its power of attraction. (Sample 25.)

These experiments indicate that the active compound is readily volatile with solvents. One seems justified in supposing, therefore, that in field tests where a preliminary evaporation of the solvent takes place, a great loss of the active material is incurred.

THERMAL TEST

In order to further determine whether the attractive substance could be obtained by heating the residue similar to that left behind in sample 25, it was heated to 150° C., no air current being used. The small amount of distillate contained much of the active substance. (Sample 26.) As no air current was used during the heating, it was hoped that if the active material were generated in the flask, it would remain there and could be obtained by adding petroleum ether and distilling it off again. The distillate made a good catch on the first day only. (Sample 27.) The final residue was inactive. (Sample 28.)

Identical original samples (30, 31, 32, and 33) were each shaken with 5 c c of concentrated hydrochloric acid overnight. The aqueous portion was distilled, made faintly alkaline with potassium hydroxide, and extracted with ether. The four samples caught only one moth, which seems conclusive evidence that the active material is destroyed by the action of concentrated hydrochloric acid.

By the time these experiments had been completed, tips were available in sufficient quantity to attempt to isolate the active compound. The most promising means to this end seemed to be fractional distillation, since the chemical nature could not be determined.

Accordingly, a filtered solution of 1,650 c c from 21,625 moths was evaporated under diminished pressure with the receiver in a freezing mixture. The last portion came over at 40° C. under a pressure of about 6 inches of mercury. The residue was distilled, and the portion that would not volatilize at 175° and 20 mm pressure was dissolved in ether and hydrolyzed with sodium carbonate solution. The ether layer was washed and evaporated and the residue steam distilled. The aqueous distillate was extracted with ether. The ether was then evaporated and residue tested. (Sample 36.) It caught no moths. It seems that the substance is either volatilized or destroyed at 175°.

One may briefly conclude, therefore, from the foregoing experiments that the attractive principle is not an acid, base, or aldehyde. It is probably an indifferent substance, as a fat, protein, or ester, and is saturated.

Cold concentrated hydrochloric acid and boiling alcoholic potash destroy the substance.

It is readily volatile with solvents, and much is lost when the solvent is removed by evaporation before the sample is placed in the field.

The long activity of extracts is probably due to the continuous generation of the attractive compound by the hydrolysis of a more complex substance. Oxidation is not concerned in the process.

Abdominal tips that have been thoroughly extracted with petroleum ether yield an additional amount of active material on hydrolysis with 1 per cent hydrochloric acid.

The samples were put out between July 21 and August 1 and remained exposed in the field for a period of 25 to 14 days. In Table 3 they are listed in the order in which they were put out. A catch of five males, or less, may be considered as negative. The catches were recorded daily, and from these the totals given in the table were obtained.

ANATOMICAL STUDIES

Studies made in 1927, 1928, and 1929 were planned (1) to get more definite information on how much of the female abdomen should be clipped into the solvents for best results, (2) to determine exactly what part of the anatomy produced the attractive substance, and (3) to obtain information which might aid in determining the exact nature and chemical formula of the attracting substance so that it might be prepared in quantity synthetically.

Various parts of the anatomy, more particularly the reproductive system, were dissected, then placed in a solvent (xylene), and put out in traps in the field. Most of the dissecting was done under distilled water, in which previous tests had shown a small portion of the active substance to be soluble. Therefore, while making the dissections, a small quantity of the active substance became absorbed by the various parts of the anatomy as they were being removed. Hence, a small number of male moths were sometimes caught by these parts (particularly in 1927) in traps which otherwise would not have caught any males. These traps were put out in heavy infestations in 1927 and in moderate infestations in 1928 and 1929. Under these conditions a catch of 12 males or less may be considered

as a negative result. After 1927 it was found that considerable dissecting could be done without a liquid; but when it became necessary to dissect certain parts under water, this was done as quickly as possible. In 1927 only a relatively small number of parts were dissected, and each sample was held in one-fourth ounce of xylene for approximately 5 days and then put in the field. In 1928 and 1929 each sample of parts was put in three-fourths ounce of xylene for approximately 10 days before being put in the field. During these two years several hundred females were dissected, so that duplicate tests of each sample of parts were made, and it is mostly from these tests that the conclusions have been drawn, instead of from the preliminary results of 1927.

TABLE 4.—*Numbers of male gipsy moths caught at traps containing dissected parts of females, 1927* [1]

Sample No.	Females used	Part of female used	Males caught	Males caught per female represented
	Number		*Number*	*Number*
1	1	Tissue at oviduct opening	82	82
2	1	Tissue immediately surrounding opening of copulatory pouch	98	98
3	3	Copulatory pouch	2	0.7
4	3	Oviduct	36	12
5	4	Accessory glands	9	2.2
6	12	Ovarian tubes	51	4.2
7	2	Rectal pouch	2	1
8	12	do	41	3.4
9	10	Liquid from rectal pouch	3	0.3
10	1	First segment (from posterior end, no part of reproductive system included).	8	8
11	15	"Tips" ground in 5 cc water, plus 1 ounce xylene	507	33.8
12	15	Large female larvae ground in 1 ounce xylene	0	0
13	15	Female pupae ground in 1 ounce xylene	0	0
14	15	Head and thorax of female moths	0	0
15	25	Abdominal "tips" alone (no solution)	5	.2
16	30	Check (living females)	848	28.2

[1] The traps were placed in the field on Aug. 1, where they remained 33 days.

It has been assumed by many zoologists that the substance which attracts males to females is produced in the accessory glands of the reproductive system. In the reproductive system of the female gipsy moth there are two accessory glands: One a small bulblike structure whose function is not known unless it is that of a seminal vesicle; and the other a large paired gland containing the substance which, upon exposure to air, cements the eggs together and to the surface on which they are deposited and which, unlike the attractive substance, does not mix or dissolve in fat solvents. The contents of both of these glands gave negative tests for the attracting substance. It is interesting that tests with the reproductive system (the accessory glands, copulatory pouch, oviduct, ovarian tubes, and eggs) yielded generally negative results, as likewise did traps containing the hairs, rectal pouch, segments of the abdomen taken after removal of the reproductive system, the thorax and head of the adult, and female larvae and pupae. The data presented in Tables 4, 5, and 6 indicate that the attractive substance occurs in the tissue immediately surrounding the opening of the oviduct and copulatory pouch, more particularly in the vicinity of the copulatory pouch opening. This tissue consisted of the genitalia, together with a very thin, narrow

band of body-wall tissue of about one-half millimeter in width. In dissecting these chitinous parts it was found that often a very small quantity of tissue that was attached to the inner chitinous surface was also removed. In most instances that portion of the genitalia pertaining to the copulatory pouch opening and that portion surrounding the oviduct opening were put out in separate traps.

TABLE 5.—*Numbers of male gipsy moths caught at traps containing dissected parts of females, 1928*

Contents of traps	First series of tests			Second series of tests		
	Females used	Days exposed in field	Males caught	Females used	Days exposed in field	Males caught
	Number	*Number*	*Number*	*Number*	*Number*	*Number*
Tissue immediately surrounding copulatory and oviduct opening	19	5	[1] 13	15	10	34
Tissue immediately surrounding copulatory opening				15	10	14
Tissue immediately surrounding oviduct opening				15	10	20
Copulatory pouch	18	15	0	15	10	0
Oviduct	17	15	6	15	10	0
Accessory gland (small bulblike)	17	15	0	15	10	0
Accessory glands (large paired)	19	15	0	14	10	0
Ovarian tubes with approximately 4,500 eggs	21	15	4	16	10	1
Eggs (approximately 4,500) alone	14	15	0	17	10	0
Rectal pouch	18	15	0	14	10	1
Liquid from rectal pouch	15	30	1	16	10	0
Dissecting water shaken with xylene	18	14	29	13	10	25
Connective tissues—thorax, etc	14	15	8	14	10	4
Hairs from abdomen	30	28	3	15	10	1
First segment from posterior end (without reproductive system)	12	14	3	14	10	5
Second segment from posterior end (without reproductive system	14	14	1	14	10	0
Third segment from posterior end (without reproductive system)	12	15	[2] 40	15	10	0
Larvae (ground)	16	15	0	16	10	0
Female pupae	13	15	3	17	10	0
Dead females about 14 days old, crushed	18	15	0	18	10	0
Blank test (tree-banding material only)	0	15	0	0	10	0
Check (living virgin females)	30	15	170	25	10	144

[1] Trap molested after fifth day.
[2] Female found ovipositing on tree under trap, which probably accounts for the results.

TABLE 6.—*Numbers of male gipsy moths caught at traps containing dissected parts of females, 1929*

Contents of traps	First series of tests [1]		Second series of tests [2]	
	Females used	Males caught	Females used	Males caught
	Number	*Number*	*Number*	*Number*
Oviduct	18	5	15	1
Copulatory pouch	16	3	12	1
Small bulblike accessory gland	19	18	15	0
Large paired accessory glands	18	1	15	1
Ovarian tubes with eggs	18	7	15	1
Tissue around oviduct opening	19	101	15	53
Tissue around copulatory pouch opening	18	161	15	137
Tissue near opening of oviduct and copulatory pouch			15	12
First segment from posterior end (without reproductive system)	16	25	15	[3] 30
Do			15	2
Second to fifth segments from posterior end (without reproductive system)	18	7	15	[3] 62
Do			15	4
Dissecting water (130 c c in xylene)	20	40	15	48
Living females (check)			16	716

[1] Traps placed in field July 26, where they remained 29 days.
[2] Traps placed in field July 30, where they remained 26 days.
[3] Results questionable, for most of the other tests of these parts gave negative results, and because these traps attracted males on the first day only. Furthermore, in 1930 a trap containing the genitalia of 15 females in xylene caught 279 males, while the rest of the abdomen of these females put out in the same way caught only 20 males.

Since the chemical tests indicated that the attractive material may arise from some fatty substance, it seemed advisable to trace roughly the metabolism of fat bodies in the larva, pupa, and adult. The healthy female larva at its fullest development has an internal cylinder of fat which surrounds the alimentary canal and lines the body cavity. In the pupal stage the fat bodies diminish as the reproductive system and eggs develop; the development of the latter taking place at the expense of the former. There is very little fat left in the body of the adult female, but there is an appreciable amount in the male. As the male is very active, it is possible that this fat may be necessary to furnish the energy expended in flight.

In conclusion, the field experiments with dissected parts strongly indicate that the active substance is not produced internally by glands in the reproductive system. Since the tissue of the reproductive system apparently is not the kind of tissue which contains fatty substances, and since previous chemical tests indicated that the substance is of a fatty nature and is soluble in fat solvents, it seems quite evident that the attractive substance is produced elsewhere. These experiments, covering a period of three years, indicate that it comes from tissue immediately surrounding the copulatory pouch. Here, it may arise from the decomposition and hydrolysis of a fatty substance. It is not unlikely that it is produced and excreted in this vicinity by ductless or hypodermal glands lying near the surface, especially since setae and pores were found here that are peculiar to this region.[14]

TESTS OF EXTRACTS

EXPERIMENTS FROM 1920 TO 1927

The principal results, up to 1927, with extracts made from female abdominal tips are summarized in Table 7. The table contains results taken from 322 traps at Saugus, Mass., covering a period of several years. The total number of males caught by each extract was obtained by adding the daily catch for the entire season. All traps, after being put out, were visited until there were no longer living males in the field. The period over which the traps were exposed in the field is important because of its bearing on the number of moths caught. Those that were exposed longest were put out

---

[14] In reviewing his own work and the work of others, McIndoo [15] wrote the following: "* * * Gazagnaire (1886) remarks that glandular cells of hypodermal origin are widely distributed in insects. They secrete the various fluids exuding through the chitin, and since their histology is so similar it might be admitted that they have the same general structure. For description, scent-producing organs may be divided into five types based on their devices for disseminating the odor and for storing the secretion as follows: (1) No special device for disseminating the odor or storing the secretion; (2) gland cells associated with hairs and scales as a means of scattering the odor more effectively; (3) "evaginable" sacs lined with hairs connected with gland cells as a device for storing the secretion and distributing the odor; (4) articular membranes serving as pouches for storing and preventing a too rapid evaporation of the secretion; (5) specialized tubes and sacs acting as reservoirs for storing and discharging the secretion." This subject is further treated by McIndoo in "Smell and Taste and Their Applications" [16], and "Communication Among Insects." [17]

[15] McINDOO, N. E. RECOGNITION AMONG INSECTS. Smithsn. Misc. Collect. 68, no. 2, p. 65. 1917.

[16] ——— SMELL AND TASTE AND THEIR APPLICATIONS. Sci. Mo. 25: 481–503, illus. 1927.

[17] ——— COMMUNICATION AMONG INSECTS. Smithsn. Inst. Ann. Rpt. 1928: 541–562, illus. 1929.

earlier than the others, and these generally caught more males than those put out later because (1) they were exposed for a longer period of time, and (2) because the flight of males reaches its peak early in the season. This condition is illustrated by experiment 1, Figure 4. This experiment, using living females as the source of attraction, was started at Saugus, Mass., July 10, 1921, and lasted 41 days. The peak, for males caught, was reached in the fourteenth day. The seasons vary somewhat from year to year, but usually the first males start issuing about July 10, and the females a few days later. An occasional male may be found as late as September 1, in the vicinity of Melrose Highlands, Mass., and later in northern New England, making a season six to eight weeks in length.

TABLE 7.—*Summary of data on experiments for trapping male gipsy moths using extracts from abdominal tips of females, 1920–1927*

Solvent	Female tips used	Age of extract	Year of test	Traps used	Days in field	Males caught
	Average	*Years*		*Number*	*Average*	*Average*
Anhydrous ether	125.9	[1] 0	1920	10	36	145.4
	348	1	1920	10	36	76
	100	2	1920	1	36	1
	25	0	1921	1	11	36
	87.5	1	1922	2	37	147
Petroleum ether	405	0	1920	9	26	84
	202	1	1920	1	36	0
	107	3	1920	1	36	2
	30	0	1921	11	28.5	141
	135	1	1922	2	37	249
	25	0	1922	1	33	127
	125	1	1923	1	37	14
	1,000	3	1923	1	37	1
Wood alcohol	25	0	1921	1	31	113
	55	1	1922	1	36	162
Ethyl alcohol 95 per cent	225	1	1921	1	40	384
	200	2	1921	1	40	240
	25	0	1921	3	39	190
Alcohol on bark	25	0	1921	2	25	213
Alcohol on cotton	25	0	1921	2	25	121.5
	122.5	1	1922	2	37	340
Alcohol on bark	25	0	1922	1	29	121
Alcohol on cotton	500	5	1923	1	30	0
	64	5	1927	1	40	671
	250	7	1927	1	40	13
	500	7	1927	1	40	397
Chloroform	25	0	1921	1	39	4
Carbon tetrachloride	25	0	1921	1	32	160
	25	2	1927	1	40	65
Benzene	25	0	1921	7	28	84
	101	1	1922	3	37	325
	25	0	1922	2	22	85
	18	0	1923	18	28	25
	13	1	1924	11	37	20
	15	0	1924	3	30	38
	30	0	1925	7	48	56
	17	0	1926	5	37	247
	30	2	1927	1	43	735
	30	1	1927	2	43	442
	18	0	1927	2	43	495
Benzene plus 10 drops tincture of civet	15	0	1927	1	43	611
Benzene and gasoline [2]	50	1	1923	1	38	87
	12	0	1923	3	38	29
Benzene and vaseline	15	0	1925	7	44	1
	30	1	1925	4	44	38
Gasoline	26	1	1923	2	38	40
	17	0	1923	10	38	35
	8	1	1924	11	38	16
	15	0	1924	2	29	13

[1] Zero indicates fresh material.

[2] Cheap grade of gasoline used in all experiments.

TABLE 7.—*Summary of data on experiments for trapping male gipsy moths using extracts from abdominal tips of females, 1920–1927*—Continued

Solvent	Female tips used	Age of extract	Year of test	Traps used	Days in field	Males caught
	Average	*Years*		*Number*	*Average*	*Average*
Xylene	20	1	1924	2	37	34.5
	15	0	1924	1	39	53
	30	1	1925	1	44	123
	15	0	1925	2	31	13.5
	17	0	1926	7	38	304
	30	1	1927	2	44	323
	16	0	1927	9	39	242
Geraniol	15	0	1927	2	36	1
Tincture of musk	0	0	1927	2	18	0
Tincture of civet	0	0	1927	2	38	54.5
Commercial vegetable oils	0	0	1927	4	36	0

In studying and comparing results, several natural conditions must be taken into account, the most important of which are (1) the degree of infestation where experiments were conducted as indicated by the checks (Table 8) and (2) the portion of the season over which the experiment is made. Extreme variations may also occur from day to day, owing to weather conditions. Cool rains, wet foliage, and temperature below 70° F. entirely stop the activity of the males.

TABLE 8.—*Average catch of males at check traps containing living virgin females, Saugus, Mass., 1920–1930*

Year	Cages	Average catch of males	Year	Cages	Average catch of males	Year	Cages	Average catch of males
	Number	*Number*		*Number*	*Number*		*Number*	*Number*
1920	2	500	1924	2	301	1928	4	335
1921	2	550	1925	1	968	1929	3	318
1922	1	1,513	1926	2	1,135	1930	1	395
1923	1	976	1927	2	1,085			

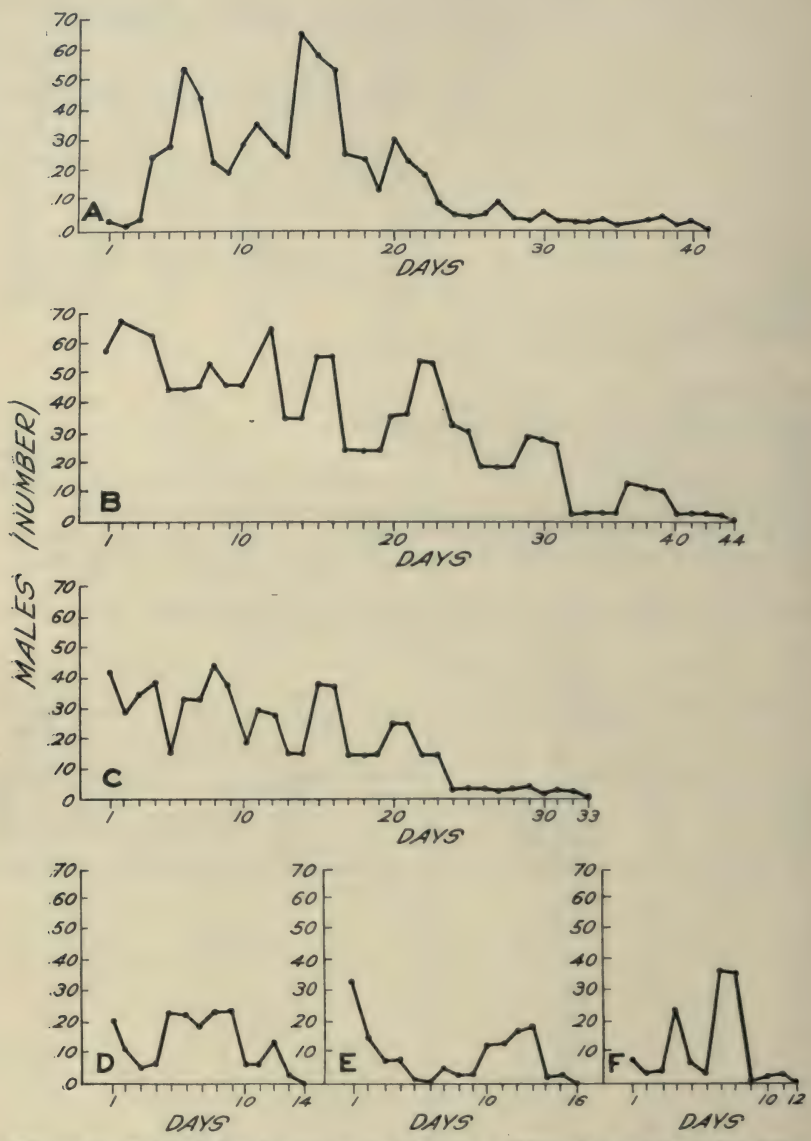


FIGURE 4.—Catches of male gipsy moths at traps at different times and under different conditions: A, Experiment 1, check, using 40 living females, July 10 to August 19, 1921, showing the beginning, height, and end of catch; B, experiment 2, check, using 40 living females, July 25 to September 6, 1927, indicating the relative abundance of males from July 25 to the end of the season; C, experiment 3, average catch of two traps containing 30 tips extracted with benzene under the same conditions as in experiment 2; D, experiment 4, petroleum ether extract of 15 tips, July 28 to August 10, 1928, showing the shortness of the period of effectiveness due to rapid evaporation and loss of the attracting substance; E, experiment 5, petroleum ether extract of 10 tips exposed by bottle method, August 1 to 16, 1928. Compare this with the same solvent by the can method in preceding experiment. The effective period was slightly longer and good catches were made, first, during the evaporation of the solvent, and then later by the residue. F, Experiment 6, anhydrous ether extract of 15 tips, July 28 to August 8; compare with petroleum ether extract in experiment 4

The area where traps were put out at Saugus, Mass., to check laboratory experiments, was a rolling wooded section of about 2 square miles, covered mostly with oak, averaging about 35 feet in height. Care was taken to place the cages or traps in the most lightly infested portion of this area in order to more nearly approach conditions prevailing in very lightly infested areas where it was expected the results might be applied. The traps were spaced approximately 150 to 200 feet apart. Table 8 gives the average yearly catch of male moths at the check traps, which contained at all times from 3 to 5 living, virgin females. As the females live only a few days, it was necessary to use from 30 to 45 living females per season for each of these traps. The trees bearing the traps were numbered (fig. 3, B) and carefully inspected to see that no natural infestation of pupae or female moths were near enough to affect the results. The results from these check traps are for comparison with the results from the extract traps when put out under similar conditions, and give a general idea of the density of infestation from year to year.

The extracts were prepared by clipping off into the solvent the posterior one to three abdominal segments of the females by means of a pair of sharp scissors. The extracts (except those carried over in cold storage) were held for a few days before being put in the field to allow for as complete extraction of the attracting substance as possible. Those referred to in Table 7 were put out by the can method. (Fig. 3.)

In a number of experiments vaseline and paraffin oil were added to the extracts for the purpose of decreasing the rate of evaporation of the active substance. In addition, geraniol, tincture of musk, a mixture of vegetable oils, soybean oil, and tincture of civet [18] were tried without the addition of female parts. Tincture of civet was also added in small quantity to benzene extract.

The catch of male moths by the various extracts increased, but not proportionally, as the number of female tips used in the solvent increased.

Of the various solvents represented in Table 7, xylene and benzene gave best results. The active substance was apparently more stable in these two solvents, since their extracts gave results that were more uniform, and attracted males over a longer period of time than did the extracts prepared from other solvents. Until 1927 one-eighth to one-half ounce of solvent was used for each experiment, but in 1927 1 ounce of solvent was used in most of the tests, and better results were secured. In 1927 the two experiments with 18 abdominal tips (fresh material) in 1 ounce of benzene caught an average of 495 males; one trap of benzene extract of 30-tip strength (1 year old) caught 442 males; and one of benzene extract of 30-tip strength (2 years old) caught 735 males. Two traps containing xylene and 30 abdominal tips (1-year-old material) caught an average of 323 males, while nine traps with fresh material of 16-tip strength under the same conditions caught an average of 242 males. The results indicated that benzene was better than xylene for preserving the material over a long period of time. That extracts of female tips deteriorate with age is clearly shown by individual experiments covering a

[18] Civet is a compound taken from the scent glands of the African civet cat.

period of years. In all cases it has been necessary to use more of the old extract to get results comparable to those given by the fresh material. The active substance has been preserved longer (seven years) in alcohol than in any other solvent. In most solvents it has not been active after the third year. It is very desirable that the active substance remain stable in storage for at least one year, since a considerable part of the extract prepared each year is being used in localities where the season is more advanced than in those from which it is necessary to obtain the female moths.

Alcohol extract gave slightly better results than the other extracts, but in either case it was necessary to use extract from a large number of abdominal tips to get a good catch of males. The results with carbon tetrachloride and chloroform were not very promising. Extracts containing one-fourth ounce each of paraffin oil, pine oil, geraniol, and vaseline gave poor results. Apparently, heavy oils retard the rate of evaporation of the attracting substance. Tincture of musk failed to catch any moths. Certain commercially prepared vegetable oils and extracts of beef fat failed to catch any moths when used in or without a solvent. A fair catch was obtained for a few days when an alcohol extract of female tips was poured on the bark of a tree.

The results with tincture of civet are very strange. When 10 drops were added to 1 ounce of xylene containing 15 abdominal tips only 15 males were caught; when 10 drops were added to 1 ounce of benzene containing 15 tips, the trap caught 611 males, next to the highest catch at any trap in 1927. When 2 drops were applied to the sticky material no males were caught; but when 2 drops were applied to cotton, 6 males were caught. When 1 c c was applied on cotton, 103 males were caught, most of which were attracted on the first day, and only 1 after the thirteenth day. In such heavy infestations an accidental catch of from 1 to 6 males sometimes occurs, allowance for which must be made in studying the results.

EXPERIMENTS IN 1928

In 1928, males were present in the field from July 20 to September 1 and were most abundant on August 2, which is about the time most of the extract traps were put out. During the season 264 traps were put out at Saugus, 161 of which were tests of extracts. The extracts were checked against one another, and against check traps containing at all times from 3 to 5 living virgin females.

Three methods of exposing the solvent and attractive substance for evaporation in the field were employed, namely, the can method previously described (fig. 3), the perforated-can method, and the bottle method. The perforated-can method resembled the can method in that the same can and cotton were used. It differed, however, in that the can was entirely closed, except for several holes punched in the bottom to permit the evaporation and escape of the solvent and attractant. The size and number of holes varied with the rate of evaporation of the solvent. The bottle method differed from the two methods just described in that the receptacle or container for the extract consisted of a 1-ounce or 2-ounce wide-mouthed bottle equipped with a cork stopper which held a glass tube in the shape of an inverted V with one end of the tube in the bottle and the

other end outside and inclined toward the ground to prevent the entrance of rain. The odors passed out of the bottle through this tube. The tubes ranged in diameter from 1 to 30 mm, depending on the rate of evaporation of the solvent; the smaller tubes being used for the solvents which evaporated rapidly and vice versa.

The value of the different solvents varied considerably, the variation depending largely on (1) their ability to extract the attractive substance from the tips, (2) their effect on the stability of the attractive substance, and (3) their volatility. If pure fat solvents (as ether, gasoline, benzene, xylene) are used, most of the attractive substance is extracted from the tips in 1 day, and practically all of it in 5 days. In one instance where the tips were allowed to remain in considerable depth at the bottom of a small vial of xylene for 3 days without being mixed, the decanted solution caught about as many males as did the tips, which were covered and extracted with xylene again after the original solution had been decanted. In a number of other instances tips have been extracted twice both by ether and xylene, but the second extraction has caught only a small number of males, and this attraction may be due to the small quantity of the original liquid not removed from the tips by the filtering. Chemical tests have indicated that a small quantity of the attractive substance may be removed from the tips with 1 per cent hydrochloric acid, after the solvent has been filtered off. The 1928 material remained under liquid from 1 to 14 days, or an average of 5 days, before being put out. When an additional substance, as an oil, was added to a solvent containing tips, the addition was made after the tips had remained in the solvents for at least 1 day, so as not to interfere with the extraction of the attractant by the solvent.

The rate of evaporation of the solvents was determined as closely as possible at the laboratory by various methods of exposing known quantities to the open air for given periods during which the temperature, humidity, and amount of surface exposed were recorded. The rate of evaporation in almost all cases was most rapid at first, becoming less rapid as more of the solution evaporated. When the can method was used in the field the more volatile solvents, as ether, benzene, and gasoline, evaporated in from 10 to 36 hours, whereas some of the heavier oils, as cottonseed oil, required more than the length of one season for complete evaporation. Evaporation through the two other methods was much slower. By using the bottle method the evaporation of any of the solvents could be extended over the entire season. Evaporation by the perforated-can method was slower than by the can method, but was much quicker than by the bottle method. The bottle method proved to be the best method for ether, which was the most volatile of the solvents tried, but was inferior to the can method for all the other solvents, especially those which volatilized very slowly.

The experiments showed that the rate of volatilization of the solvent influenced the rate of volatilization of the attractant, e. g., when the solvent used was petroleum ether or ethyl ether, males were attracted for only about two weeks; but when benzene or xylene (which evaporates more slowly) was used as the solvent, males were attracted for as long as four weeks. (Fig. 4, experiments 3, 4, 5, and 6.) Although some of the attractant is given off during the

evaporation of the solvent, most of it is given off from the residue after the solvent has evaporated. An example of this is shown graphically by experiments 3, 4, and 5, in Figure 4. One ounce of benzene was used with 30 tips in experiment 3, 1 ounce of petroleum ether with 15 tips in experiment 4, and 1 ounce of petroleum ether with 10 tips in experiment 5.

In experiment 5 the extract was evaporated by the bottle method and in experiments 3 and 4 by the can method. All of the solvent evaporated in less than one day in the case of experiments 4 and 6, and in about two days in the case of experiment 3, so at least 80 per cent of the total catch was made by the residue. In experiment 5 the rate of evaporation was reduced so that all of the solution was not evaporated until the sixth day, the catch after the sixth day being made by the residue. By reducing the rate of evaporation in experiment 5 the catch was nearly equal to those in experiments 4 and 6, and the period of catch slightly extended, although only 10 tips were used in experiment 5, as compared to 15 in experiment 4. The slow rate of volatilization of the attractant makes necessary the exposing of considerable surface in order to get a good catch of males. It is also quite evident from the daily-catch charts for 1927 and 1928 that when more than a few drops of oil was added to the solvent the rate of evaporation of the attractant was so retarded as to greatly reduce the efficiency of the extract. These observations support the view that the attractant is given off over a long period in the field by the hydrolyzing agent of the air. Among compounds that can be hydrolized are esters, proteins, and fats.

It is possible that over half of the attractant is lost from the extract while the males are not flying, since under most optimum weather conditions they are active for only about 9 hours out of 24 (9 a. m. to 6 p. m.). The most efficient means of liberating the attracting substance, if such were possible, would be to have all of it given off only during the time the males were active.

The promising results obtained in 1927 with tincture of civet, with and without the addition of female tips, suggested the use of a quantity of this material in 1928. Accordingly, civet, tincture of civet, and a synthesized product similar to civet were tried. As the chemical formula of this last (according to the chemist through whom this material was obtained) was not unlike that of oleic acid, many oils of this nature were tested. It was hoped that some substance might be found near enough like the attracting substance to either attract males without the addition of tips or increase the attraction when added to extracts containing tips. However, in all of the tests with civet and other compounds tested without the addition of female abdominal tips, negative results were obtained.[19]

A summary of the results from the more important experiments is as follows: Four traps containing 35 tips each of 1-year-old material in xylene caught an average of 194.5 males, and five traps of fresh

[19] The following substances, which gave poor to negative results, were exposed by themselves and in mixtures with various other substances both with and without the addition of tips: Tincture of civet, civet, oleic acid, cottonseed oil, amyl acetate, banana oil, corn oil, ethylamine, methylamine, benzonitril, quinoline, pine oil, oil of citronella, catnip oil, acetone, cheap gasoline, kerosene, cows' cream and yeast, honey, egg albumen, uric acid, and a mixture of all the materials listed above. A small quantity of hydrochloric acid, ammonium hydrate, water, and calcium carbonate were added separately to various substances.

material containing 15 tips caught an average of 361.5 males. Four traps with 30 tips of 3-year-old material in benzene caught an average of 140 males, and four traps of the same proportions of 1-year-old material caught an average of 224 males. These 17 traps were put out in an infestation known to be slightly heavier than that used for the other tests. The solvent which gave best results for fresh material in 1928 was a mixture of one-fourth ounce butyl acetate and three-fourths ounce of xylene, which caught 361 males, as against 350 caught by the check trap for that vicinity. High-test gasoline was the other outstanding solvent when 15 tips were used in 1 ounce of liquid. One trap of this strength caught 329 and the other 306 males in 34 days. Apparently 15 tips of fresh material, or 25 to 30 tips of 1-year-old material, per trap, is economically the best number for use in light or doubtful infestations. Three-fourths to 1 ounce of solvent per trap has given better results generally than other quantities.

EXPERIMENTS IN 1929

In 1929 the traps were put out by the can method, except where otherwise indicated, in a very lightly infested area at Saugus. Fifteen female abdominal tips were used in each case. Two traps with one-fourth ounce of butyl acetate in three-fourths ounce of xylene caught 149 and 204 males, averaging 176.5. When other proportions were tried the efficiency was reduced, as in 1928. Three traps with 1 ounce each of high-test gasoline caught 94, 190, and 203 males respectively, averaging 162.3 males per trap, whereas one trap with 2 ounces caught only 23 males. Two traps with a "special" gasoline caught 85 and 237 males, respectively, averaging 161. The gasoline was cheaper than the other solvents. Two traps with 2 and 1 ounces of benzene caught 122 and 182 males, respectively, averaging 152, and five xylene traps with 1 ounce of xylene each caught an average of 103 males. As the season began early and ended early not many moths were caught after August 15. Table 9 gives the more important results of the 1929 extract tests.

TABLE 9.—*More important results of experiments with attractants for the male gipsy moth, Saugus, Mass., 1929*

Solvent media (kind and quantity)	Date put in field	Days in field	Males caught
		Number	*Number*
High-test gasoline, 2 ounces [1]	July 19	37	23
High-test gasoline, 1 ounce	do	37	94
	July 22	35	190
	do	35	203
Average			162.3
High-test gasoline, 1 ounce (bottle method)	July 24	33	26
A special motor gasoline, 1 ounce	Aug. 10	15	237
Special gasoline, 1 ounce	July 20	35	85
A slow-burning gasoline, 1 ounce	do	35	43
	Aug. 10	15	8
Xylene, 1 ounce	Aug. 20	37	30
	July 19	37	87
	July 24	33	99
	July 23	34	138
	July 29	27	161
Average			103

[1] 15 tips or parts of abdomens of females used for each test except when stated otherwise.

TABLE 9.—*More important results of experiments with attractants for the male gipsy moth, Saugus, Mass., 1929*—Continued

Solvent media (kind and quantity)	Date put in field	Days in field	Males caught
		Number	*Number*
Xylene, 1 ounce, last segment of abdomen	July 22	35	62
Xylene, 1 ounce, last two segments of abdomen	do	35	115
Xylene, 1 ounce, whole abdomen	July 24	33	104
Xylene, 1 ounce, second and third segments from posterior end	do	33	16
Benzene, 2 ounces	July 19	37	122
Benzene, 1 ounce	do	37	182
Benzene, 1 ounce (bottle method)	July 24	33	9
Butyl acetate, one-fourth ounce, xylene, three-fourths ounce	do	33	204
	do	33	149
Butyl acetate, one-half ounce, xylene, one and one-half ounces	Aug. 7	18	90
Butyl acetate, one-eighth ounce, xylene, seven-eighths ounce	July 24	33	76
Butyl acetate, one-fourth ounce, benzene, three-fourths ounce	do	33	41
Butyl acetate, one-fourth ounce, high-test gasoline, three-fourths ounce	do	33	66
Amyl acetate, one-fourth ounce, xylene, three-fourths ounce	do	33	75
Quinoline, 5 c c (bottle method) [2]	do	33	0
Quinoline, 5 c c (can method) [2]	do	33	0
Civet, 1 g, on cotton [2]	do	33	0
Tincture of civet, 1 ounce [2]	do	33	0
Tincture of civet, 1 ounce (1-year-old material)	July 12	54	15
Check (average of three traps containing 34 living virgin females)			318

[2] Material in trap contained no tips.

Twenty-one traps were put out in 1929 with material that had been held in storage at an average temperature of about 2° C. for one year. None of the traps made a good catch, and only one caught a fair number (105) of males. The liquid portions consisted of xylene, benzene, gasoline, alcohol, petroleum ether, anhydrous ether, acetone, pine oil, catnip oil, oil of citronella, and tincture of civet, and contained from 15 to 30 abdominal tips per ounce. The material had been put in quart jars, the tops fastened down on rubber gaskets by clamps, and the jars kept in cold storage. A considerable proportion of the rubbers were affected by the solvents, and the evaporation from the different jars ranged from 0 to 60 per cent. The only liquids that did not undergo noticeable evaporation were pine oil, catnip oil, and oil of citronella. It seems likely that much of the attractive substance escaped from the jars in the same way as did the solvents, hence reducing the efficiency of the material. Capping the containers with cork stoppers wrapped with tin foil and sealed over the top with gelatine caps proved to be the best apparent remedy for preventing evaporation and leakage of gas or attractive substance during storage.

An attempt was also made to reduce the possible loss due to deterioration in storage by decanting the liquid from the tips and storing it separately until ready for use in the field. When the tips are left in the solvent it is possible that deterioration may result from such impurities as hair, excreta, fat, eggs, and chitin. When fresh extract containing rubber stoppers or iron rust was put out the attractant was apparently affected, as very few males were caught.

RESULTS WITH VARIOUS ABSORBENT MATERIALS

Six experiments were conducted in 1929 to obtain more data on the value of different absorbents in holding and releasing the active substance. Good absorbents should cause as little deterioration as

possible. The can method with 15 abdominal tips was used in each case. Cotton was used in two of the traps, with 1 ounce of xylene as the solvent. In one case the cotton was packed tight in the can and in 37 days 73 moths were caught, whereas 187 moths were caught by the other trap with the cotton loosely packed. (Traps 41 and 42, Table 10.)

Traps 76 and 77 contained, respectively, 1 ounce of benzene and 1 ounce of gasoline extract poured over washed wool, but most of the solution dripped to the ground and only 55 and 30 moths, respectively, were caught in 30 days. In trap 82 only one-half ounce of gasoline was tried, and the wool allowed to soak in it overnight so that no loss by dripping occurred. This trap was put out August 9, after the period of maximum abundance of the moths. It remained in the field 20 days and caught 189 males, which is a favorable record under adverse conditions.

Kieselguhr or infusorial earth, which is an inert powder with good qualities as an absorbent and filter, was tried with 1 ounce of gasoline extract. The kieselguhr was held in place in the inverted can by a piece of cheesecloth stretched across the mouth of the can. (Trap 83.) Like trap 82, this trap was put out (August 7) after the maximum abundance of the moths had passed. The trap was in the field 22 days and caught 110 males. All except two of these moths were caught in the first four days. As rain wet the material through the cheesecloth within a few days after the experiment was begun, it is possible that it cut down the period of catch and incidentally the total catch. The results of these experiments are not final, but they indicate possibilities of finding a good absorbent by testing the value of various kinds and quantities of absorbent material. The results are given in Table 10.

TABLE 10.—*Tests of absorbent materials for holding extracts attractive to the male gipsy moth, 1929*

Absorbent used	Solvent media (kind and quantity)	Trap No.	Days extracted	Date put in field	Days in field	Remarks	Males caught
			Number		*Number*		*Number*
Cotton	Xylene, 1 ounce	41	8	July 24	37	Packed tightly in can	73
		42	8	do	37	Packed loosely in can	187
	Benzene, 1 ounce	76	3	July 31	30	Nearly all of solution dripped to the ground.	55
Washed wool	High-test gasoline, 1 ounce.	77	3	do	30	do	30
	High-test gasoline, ½ ounce.	82	6	Aug. 9	20	Extract poured in can, covered and allowed to soak for one day before putting out. Put out late.	189
Kieselguhr held in can by cheesecloth.	High-test gasoline, 1 ounce.	83	4	Aug. 7	22	Caught 108 moths in four days. Put out late. Very few moths flying.	110

TEST OF AGE OF FEMALES

Eight traps put out in 1929 with extracts from females of various ages yielded results that were interesting though subject to some uncertainty owing to the small number of tests. Experiments were

conducted with abdominal tips clippd when the females were 1, 3, and 6 days old, one trap with tips from dead females 10 days old, and one with tips from female pupae. The tips were left in the solvents from four to seven days. No males were caught when tips from pupae or from females that had died naturally from old age were used. Of the other tests, extracts prepared from females 1 day old caught an average of 49 males, that from 3-day-old moths caught an average of 143.5 males, that from 6-day-old moths caught an average of 230.5 males. These results indicate that increased age, up to a certain point, greatly increased the amount of the attractive substance stored up in the females. The gasoline extract caught slightly more moths in each of the three instances than did the xylene extract. The three traps containing xylene caught a total of 403 males during the season, while the same number of traps containing high-test gasoline extract caught 443 males in a period several days shorter. The results are given in Table 11.

In 1931, 38 traps were put out with extracts from females that had just emerged. The results from these traps were compared with those from more than 38 traps containing extracts from females 2 to 6 days old. In all cases extract from females 1 to 4 days old caught at least 10 times as many males as extract from females that had just emerged when their tips were removed.

TABLE 11.—*Tests of extract prepared from abdominal tips of females of various ages, 1929*

Solvent media [1]	Date put in field	Days in field	Age of females	Males caught
		Number	*Days*	*Number*
Xylene	July 22	42	10 (dead)	0
	do	42	[2]	0
	do	40	1	48
High-test gasoline	July 29	33	1	50
Xylene	July 22	40	3	139
High-test gasoline	July 29	33	3	148
Xylene	do	33	6	216
High-test gasoline	do	33	6	245

[1] 15 female tips in 1 ounce of solvent used in each of these tests.
[2] Pupae were used in this test.

In 1930 several traps were put out with extract from females that had just emerged. A few of these traps caught no males, and none of the others caught more than a few. Several other experiments to determine the effect of age of virgin females indicated that the amount of attractant in the females increased for at least one day. It was found best not to keep them more than four days, as after that they began to die.

It is interesting that females seldom, if ever, mate twice or attract males after once mating, whereas virgin females afford strong attraction for males as long as they live. Twenty females were caged and records made of the daily catch and time of death. The last female to die lived 17 days and attracted males until death. A trap with extract from females that had just mated caught 129 males, whereas a trap of similar extract from females that had not mated caught 233 males. A trap with extract from females that had mated

and laid eggs two days prior to the removal of their tips caught only 30 males, but extract from females that had mated from four to seven days previous to the removal of their tips caught no males. Extract from virgin females, two to six days old, caught many males, and an extract containing 15 female tips and 15 male tips caught 239 males, whereas an extract containing 15 male tips alone caught none.

RESULTS OF OTHER TESTS AT SAUGUS, MASS.

In 1930, 25 traps of 1929 material that had been held in cold storage for one year, and 97 traps of fresh 1930 material were put out. These traps caught a total of 11,624 males. The results from the more important solvents held in storage are given in Table 12. Observations indicated that extracts of tips of females that were less than 12 hours old did not give good results, but one trap containing only 15 tips in xylene from females approximately 24 hours old caught 214 males, which is about equal to the catch with fresh (1930) material. Six traps containing tips from females less than 12 hours old in high-test gasoline caught an average of only 8 males. It is not known whether this result was due to the females not being old enough at the time the tips were removed or to a lack of stability of the attractant in this solvent under the cold-storage conditions. The storage containers were sealed with cork stoppers wrapped in tin foil and covered with gelatin caps, and no noticeable loss of extract by evaporation could be observed.

TABLE 12.—*Tests of attractant material that had been held in cold storage for one year, Saugus, Mass., 1930*

Solvent	Female tips per trap	Traps	Age of females	Average catch
	Number	*Number*		*Number*
High-test gasoline	15	3	Less than 12 hours	6
	30	3	do	10
Xylene	30	4	do	44
	15	1	Less than 24 hours	214
Benzene	15	2	Less than 12 hours	73
	30	1	Less than 24 hours	173
	15	1	do	187
Butyl acetate one-fourth ounce, xylene three-fourths ounce.	15	1	24 to 48 hours	144

In the tests made at the same time with the fresh material the females from which the tips were obtained were at least one day old but not over four days old. Each trap contained 15 tips in 1 ounce of solvent, and all were put out under practically identical conditions.

The results of these tests are as follows: Two traps with gasoline from the Texas oil fields as a solvent caught an average of 292 males; two traps with a special motor gasoline caught an average of 254 males; and six traps with a high-test airplane gasoline [20] caught an average of 240 males. One trap with toluene as

[20] As the distillation points of lots of the same brand of gasoline are apt to vary, it has been the practice during the last two years to purchase two or three 25-gallon samples from different lots, and any one of these proving to be a good solvent will furnish a supply sufficient for several years.

the solvent caught 245 males; eight traps with xylene as the solvent caught an average of 196 males; and two traps with benzene as the solvent caught an average of 152 males. Two check traps, with approximately 30 living females each, caught an average of 494.5 males.

In one experiment the genitalia and tissue immediately surrounding the opening of the copulatory pouch and oviduct of 15 females was put out in one trap, and the last three abdominal segments of the same females without the tissue used in the trap just mentioned put out in another trap. The former trap caught 279 males and the latter 20.

As in previous years the traps of 1931 were spaced 100 to 200 feet apart along trails in a forest area of approximately 600 acres. One hundred and fifty-one traps were put out, or about one trap to 4 acres. A total of 7,833 males were caught, an average of 51.87 per trap, or about 13 per acre. The infestation was extremely light, for only two egg clusters were seen during the daily visits to the traps, and two men collecting for three hours were able to find only 12 pupae (11 male and 1 female). The fact that more male than female gipsy moths reach the adult stage in the field makes it easier to locate infestations by trapping than if the reverse were true.

In 1931 a double-funnel or double cone-shaped trap was devised. It turns easily on an axis in such a way as to hold the point of one cone toward the wind, and the other cone in the opposite direction. About 90 per cent of the males trapped were caught by the cone with the point toward the wind.

OBTAINING FEMALE ABDOMINAL TIP MATERIAL

The development of methods that will permit the coverage of a greater area with traps, and at a lower cost, is an important research problem. There are two methods of attack: One is improving the quality of the extracts and methods of exposing in the field so that the traps will be more dependable and so that a given amount of material can be made to cover a greater area. This requires the discovery and use of the best solvents, clipping the tips when the females reach the age at which they yield the greatest quantity of attractive substance, prevention of evaporation and deterioration in storage, and the development of better traps. The other is obtaining a larger number of female moths, which may be accomplished by either one or by both of two ways, i. e., by improving collecting methods and increasing the collecting force, or by increasing the percentage of emergence from the pupae collected. Table 13 shows that 945,314 pupae collected yielded only 148,965 moths, which is an issuance of 15.8 per cent, or about 1 moth for each 6 pupae. This mortality of 84.2 per cent was due to disease, parasites, and to unknown causes. Considerable loss results from handling large amounts of material. If by improved handling methods the ratio of issuance could be increased to 2 moths for each 6 pupae, instead of 1 out of 6, it is at once obvious that the area to be covered could be doubled. During some years the pupae were collected in small shallow boxes and transported to a central collecting station where they were spread out in thin layers on the floor (fig. 5) or in trays (fig. 6), and the female abdominal tips clipped daily as the moths issued. The amount of

available material varies from year to year owing to natural control factors and facilities for collecting.

TABLE 13.—*Data on collection of female pupae and the number of moths obtained*

Year [1]	Pupae collected	Moths issuing		Remarks
	Number	*Number*	*Per cent*	
1920	340,800	30,929	9.1	Collected by 8 men working 19 days.
1923	225,075	26,500	11.8	Collected by 8 men in 21 days.
1925	79,439	24,560	30.9	
1928	300,000	66,976	22.3	Collected by 8 men in 21 days.
Total	945,314	148,965	15.8	

[1] In 1924 a total of 34,860 moths were obtained; but as the exact number of pupae from which these issued was not recorded, they have not been included in the tabulations.

In 1929 a small box, with two sliding drawers that were divided into many small partitions in which the pupae were placed, was used for collecting. An increased percentage of emergence was obtained,

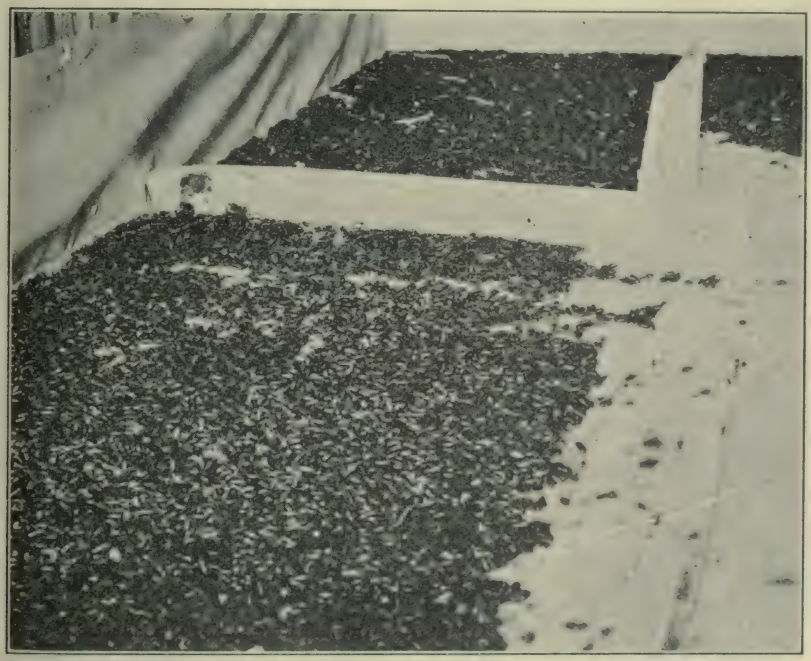


FIGURE 5.—Female gipsy-moth pupae spread out on canvas. As the moths issued and crawled up the canvas sides they were picked off and the tips of their abdomens removed

but this value was offset by the fact that the rate of collecting was reduced. In 1931 the method of collecting and rearing pupae was greatly improved, and many more moths were obtained then than in previous years. The pupae were carefully removed from the trees and placed between thin layers of cotton batting in the trays of collecting boxes, and carried to a ventilated room of near-cellar tem-

perature ranging from 60° to 75° F., close to the collecting point, where they were transfered in the cotton layers to large, coarse, wire screened trays supported by large racks. By this method of handling, the pupae were allowed to become entangled in and attached to the

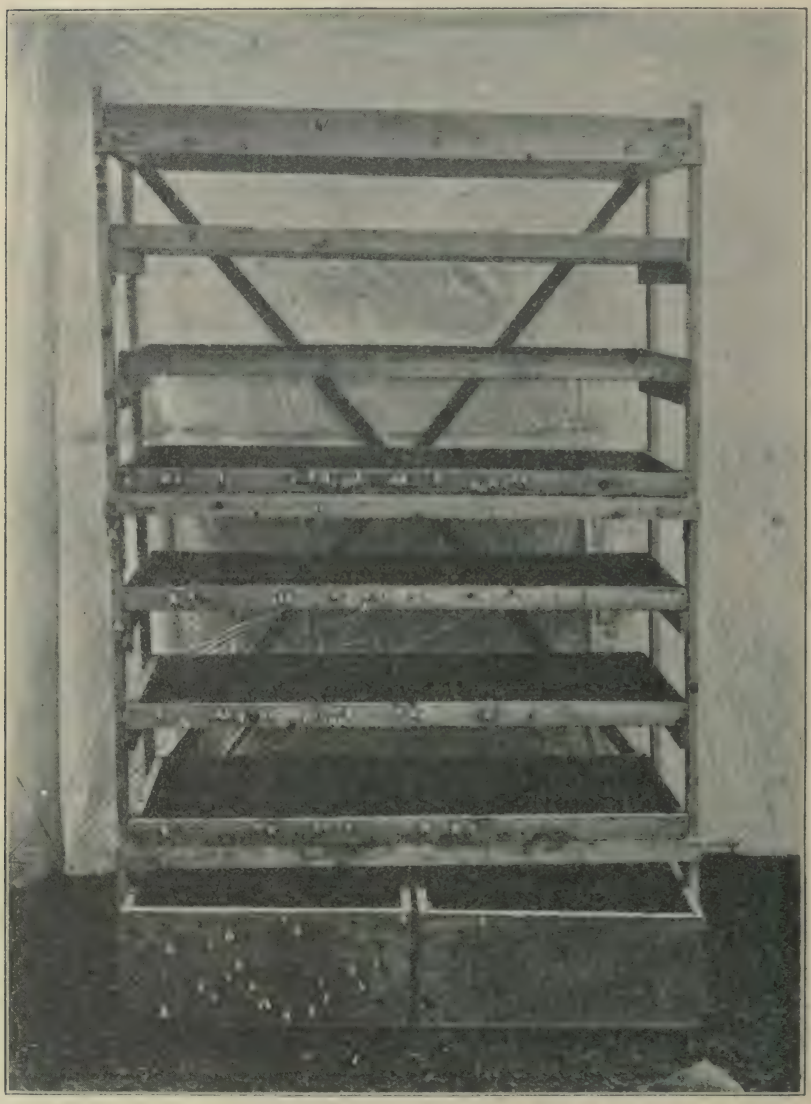


FIGURE 6.—Female gipsy-moth pupae spread out in coarse-wire screened trays. The moths are removed and counted soon after emerging. The two boxes at the bottom of the rack contain moist earth into which larvae of the parasite *Sturmia nidicola* Towns. fall and are saved and later returned to the field

cotton fibers in much the same manner as they were found naturally on the tree. The layers of cotton also helped to prevent injury by crushing. By having the rearing place at or near (within 5 miles of) the point of collection, injury by transporting bulk collections long

distances (as 60 miles or more) was reduced to a minimum, and the cool room used for rearing prevented loss by hot, dry air. The females were counted and held for one to two days before their tips were removed.

Other collections of pupae were made as follows, and transported for about 60 miles by truck to the Melrose Highlands, Mass., laboratory and placed in a shaded screened cage: 2,173 on cotton layers as described above, 5,560 on sawdust, 3,800 on cotton in a partitioned box similar to an egg crate, and 1,550 on wool layers. Because of improved methods of handling, a good issuance was obtained in all cases. The percentages of pupae giving moths were as follows: On sawdust 38, on cotton 42, on wool 50, and on cotton in the partitioned crate 52. Only 11 per cent of the pupae had become moths in 1930, owing to a greater mortality from parasites and disease than in 1931, and to imperfections in the handling methods which were eliminated in 1931.

One thousand nearly mature female larvae were collected in 1931 and fed oak leaves until they pupated. Although considerable wilt disease developed, an issuance of 19 per cent was obtained.

The following figures will show the quantity of material needed to cover a given area in case it were advisable to use attractants on a large scale: In 1928 eight men collected 300,000 female pupae in 21 days, from which 66,976 moths issued as available abdominal-tip material. This made enough extract for 2,233 traps at 30 tips per trap, or 4,465 traps at 15 tips per trap. As the average town has about 70 miles of road, this amount of extract would cover 8 towns, if "30-tip" strength were used in traps one-fourth mile apart. If "15-tip" strength were employed, 16 towns could be covered, and still larger areas by putting the traps farther apart. In all towns, however, there are large areas with little or no tree growth so that the possible infested area that could be covered is greater than is represented by the above figures.

USE OF EXTRACTS TO LOCATE NEW INFESTATIONS IN NEW ENGLAND

A varying number of extract traps were put out in New England at or near the quarantine line each year from 1923 to 1929. Those put out in 1923, 1924, and 1925 gave very poor results. In Essex, Vt., only one male was attracted in 1924, and in Sheffield, Mass., only one in 1925. In a few cases infestations existed within one-half mile of traps that attracted no males. A small quantity of vaseline was added to the benzene extract in 1925 to prevent the solution from evaporating so rapidly, but this proved detrimental. Better results were secured as improvements of the extracts were made, and in 1926 a large number of traps were put out. The numbers of males caught are shown in Table 14.

TABLE 14.—*Summary of catches at extract traps at or near the New England quarantine line, 1926*

Location	Egg masses found		Distance to nearest traps	Solvent	Males caught
	Old	New			
	Number	*Number*	*Miles*		*Number*
Norfolk, Conn.	3	1	½	Xylene	0
			¾	do	1
North Canaan, Conn.	3	29	¾	Benzene	1
			¼	Xylene	0
			¼	do	0
			½	Benzene	0
	1	1	½	do	0
			½	do	0
Sheffield, Mass.	10	20	½	do	0
			¾	do	0
	6	7	⅝	do	0
			¾	do	1
			⅛	Xylene	1
			½	do	0
Sandisfield, Mass.	40	26	⅝	do	1
			¾	do	0
			¾	do	0
			¼	do	0
	5	55	¼	do	3
Barkhamstead, Conn.			½	do	4
	5	8	½	do	5
			⅝		
Canton, Conn.	1	2	½	do	10
		473	¾		
		3	⅛	Xylene	8
	39	30	⅜	do	8
	22	140	⅜	do	10
Granby, Conn.	12	29	¼	do	16
	190	900	⅜	do	10
	425	495	½	do	0
	2	1	½	do	1
		1	1⅛	do	1
Colebrook, Conn.	8	1	5/16	do	0
			⅝	do	0
			½	do	1
Simsbury, Conn.	3	12	⅝		0
			⅞		1
	12	86	1/16	Benzene	1
	37	538	¼	do	1
			¼	do	1
			⅝	do	0
	12	24	⅛	do	0
Essex, Vt.			¼	do	6
	4	24	1/16	do	0
	22	76	½	do	2
	5	43	7/16	do	0
			1/16	do	0

Table 14 shows that both positive and negative results were secured. Twenty-three traps that were within 1 mile of infestations attracted 1 or more males, whereas 21 traps within similar distance from infestations did not catch males. At many traps catches of from 1 to 16 males were made, and subsequent scouting revealed infestations of one or more newly deposited egg masses. The larger catches of 8, 10, and 16 males, respectively, per trap were made in Granby and Canton, Conn., where the infestations were one-half mile, or less, distant. The cages were not attended daily, and the males were removed at the end of the season; consequently no relation could be observed between the catches and the prevailing winds to determine why several of them did not attract. It is possible that alternate-year changing of the trap locations in each vicinity might take care of much of this variation.

USE OF EXTRACTS IN NEW JERSEY

In 1920, when the gipsy moth was first found in New Jersey, 21 traps containing extract of abdominal tips of females were put out near the center of the original colony and a few miles distant. This was done to ascertain whether this method would be of help in locating new colonies.

Material preserved in 1917 and 1919 in 95 per cent alcohol or in petroleum ether was used. Strong dosages were used, ranging from 2 to 4 teaspoonfuls of extract, representing from 215 to 479 abdominal tips, which proved to be more than was necessary. A total of 85 males were caught in 14 of the 21 traps. Two of the traps containing alcoholic extract attracted 18 and 23 males, respectively. These held a higher concentration, however, than the contents of those of petroleum ether, the best of which attracted seven males. Subsequent scouting showed that there were scattered gipsy-moth colonies throughout the section where the traps were put out, and in some cases a colony within a few hundred feet of the trap.

The object of the campaign against the gipsy moth in New Jersey was to exterminate the insect. The material used in these traps was necessarily collected and preserved in New England the summer previous to its use in New Jersey, as the season is earlier in New Jersey. The abdominal tips were later preserved in gasoline, xylene, and benzene, which were found to be the better solvents. The 1-year-old material was used at the rate of 30 to 40 female abdominal tips per trap.

The field scouting in New Jersey was very carefully done each year, and the scouting in 1924–25 resulted in the finding of some colonies in the vicinity of traps that did not attract any males in the summer of 1924. The following statements give the results of the scouting about these traps and the solvents used:

Hillsboro. Infestation of 10 new egg masses found in Franklin Township, five-eighths mile from cage containing benzene and crushed tips.

South Brunswick Township. Infestation of 35 egg masses found one-eighth mile from cage containing gasoline and uncrushed tips. Infestation of three new egg masses found five-eighths mile from cage with benzene and crushed tips.

Bridgewater Township. Infestation of one new egg mass found seven-sixteenths mile from cage with benzene and uncrushed tips. Another cage containing gasoline and crushed tips was also located seven-sixteenths mile from the above infestation. Infestation of one egg mass found 100 and 150 feet from two cages containing gasoline and crushed tips.

The results of the above attempts were all negative, and it is impossible to explain this satisfactorily unless it was due to the deterioration and evaporation of the extract in storage and in transit. Improvement of extracts and methods in general have been made, and more encouraging results were obtained in New Jersey with the 1926 experiments, as is shown by Table 15.

TABLE 15.—*Results of experiments with benzene extracts to attract male gipsy moths in New Jersey, 1926*

Township	Egg masses found		Distance of nearest cage	Males caught
	Old	New		
	Number	*Number*	*Miles*	*Number*
Bridgewater	33	88	1¼	1
	19	5	⅜	2
			1	2
			1¼	1
Hillsboro	4	3	¾	1
Bernard	0	3	5/8	1
Warren	33	88	1[1] ¾	1
	4	7	1¼	1
	47	68	⅞	1
	1	4	[2] 1 1/16	1
	12	10	([3])	2
Total	153	276		14

[1] Another nearer cage failed to attract.
[2] Two nearer cages failed to attract.
[3] At cage.

Table 15 shows that 14 males were caught. This information proved of considerable value to the eradication project, especially since three traps located in parts of the townships of Bridgewater, Bernard, and Warren, which recent records had indicated were free of the gipsy moth, attracted one male each. A catch of three males in a heavily wooded locality indicated the presence of one or more infestations in the neighborhood. Some special scouting was done, and a colony of 33 old and 88 new egg masses was found within 1¼ miles of the traps attracting. Instead of being left to further reproduce until plans for scouting materialized, the colony was immediately treated, and then sprayed in 1927. Other colonies were also found nearer than this to the attracting cages, as shown in the table. Some of the traps did not catch any males, and no colonies were found in these localities. Since 1927 very few colonies have been discovered in New Jersey, and in 1930 and 1931 none were found.

SUMMARY

Male gipsy moths are strongly attracted to living virgin females. A scent is given off from the vicinity of the copulatory-pouch opening and is sensed by the male through its antennae.

Some males fly as far as 2.38 miles, but usually the distance of flight is much shorter; and catches of males are seldom made at traps over one-half mile distant from a colony. The percentage of released males recovered is dependent upon a number of factors, such as distance, wind, temperature, and topography.

Certain extracts made from the region of the female genitalia attract males, for the attractant is soluble in a number of fat solvents, as ether, benzene, xylene, and gasoline. None of the attractant was found in glands of the reproductive system internally, although in the vicinity of the copulatory-pouch opening setae and pores peculiar to this region were found, and it is possible that the attractant arises here, for extracts of this portion of body-wall tissue attracted many males. The attractant is of a complex fatty nature,

and is saturated. When exposed, it is active for several weeks, a period equivalent to the flight season of the males—owing to the continuous generation of the attractive compound by hydrolysis. It is fairly stable under present storage methods, and from two-fifths to three-fifths of its value is retained at the end of one year.

At the moment the female emerges little attractant can be extracted, but the quantity rapidly increases thereafter for at least one day. Virgin females attract males as long as they live, but females that have mated generally do not attract them. Although considerable of the attractant may be extracted from females soon after they have mated, the quantity rapidly decreases.

The percentage of female moths obtained from bulk pupal collections was greatly increased by placing the pupae between thin layers of cotton or wool batting in partitioned collecting boxes, and then transferring them to a ventilated room of moist air at a temperature of 60° to 75° F. The room should be located near the point of collection to prevent injury in transporting them long distances. The best results were obtained when the moths were allowed to age for two days before the tips were removed.

Results indicate that the practical value of extract traps may be improved further by (1) increasing the number and proportion of female moths obtained from available pupae, (2) removing the female abdominal tips at the age when they yield the greatest quantity of the attractive substance, (3) improving the extracts, (4) preventing deterioration in storage, and (5) determining the best method and best absorbent material for exposing the extracts in the field.

The use of an extract in the traps instead of living females has the following advantages: (1) The extract can be preserved for one or more years and be available for use in newly infested localities where the season is earlier than in the place from which living females would have to be obtained, (2) it is not necessary to visit the traps except to put them out and remove them at the end of the season, and (3) the danger of starting new infestations is eliminated.

Some new and important infestations in the border of the infested territory and in New Jersey were discovered by the use of traps containing extracts of female abdominal tips.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Entomology	C. L. MARLATT, *Chief.*
Division of Forest Insects	F. C. CRAIGHEAD, *Principal Entomologist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 335 NOVEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

FERTILIZERS FOR SWEETPOTATOES BASED ON INVESTIGATIONS IN NORTH CAROLINA

By J. J. SKINNER, *Senior Biochemist, Division of Soil Fertility, Soil Investigations, Bureau of Chemistry and Soils,* and C. B. WILLIAMS, *Head, Department of Agronomy,* and H. B. MANN, *Associate in Soil Investigations, North Carolina Agricultural Experiment Station*

(The Bureau of Chemistry and Soils in Cooperation with the North Carolina Agricultural Experiment Station)

CONTENTS

	Page		Page
Introduction	1	Potash sources	23
Fertilizer ratio experiments	3	Fertilizer placement and time of application	25
Plan of experiments	3	Concentrated fertilizers	34
Soil types and results obtained	4	Discussion	43
Discussion	15	Summary	43
Different quantities of fertilizers	18	Literature cited	45
Nitrogen sources	20		

INTRODUCTION

With an increase in the production of sweetpotatoes in North Carolina, interest has developed in fertilizer problems pertaining to this crop. The area in sweetpotatoes in the State in the 5-year period, 1924–1928, averaged 83,000 acres annually, which exceeded the acreage in any other State except Georgia and Texas. (*18*)[1]. The average production of sweetpotatoes in North Carolina from 1924 to 1928 was 7,989,000 bushels annually, which was exceeded only by Georgia. In 1929 there were produced in North Carolina 9,126,000 bushels of sweetpotatoes, having an estimated value of $8,213,400, and in 1930, 9,506,000 bushels, having an estimated value of $8,555,000. The production in North Carolina in 1930 was larger than in any other State.

The average annual acre yield of sweetpotatoes in North Carolina for the 10-year period, 1919–1928, was 101 bushels, for 1929, 117 bushels; and for 1930, 97 bushels. The average annual acre yield of all the producing States for this 10-year period was 95.2 bushels; for 1929, 102.9 bushels; and for 1930, 84.9 bushels. The average acre yield of sweetpotatoes in North Carolina for the 10-year period, 1919–1928, was exceeded by 13 States, in 1929 by 11 States, and in 1930 by 23 States. The average acre yield of 4 States in 1929 was 140 bushels or more.

Sweetpotato growers in North Carolina, faced by the necessity of producing larger acre yields at lower cost and confronted with difficulties in securing good stands, although using large applications of

[1] Italic numbers in parentheses refer to Literature Cited, p. 45.

130350°—32——1

commercial fertilizers, appealed to the North Carolina Agricultural Experiment Station and the United States Department of Agriculture for assistance. This interest on the part of growers resulted in the establishment of cooperative fertilizer experimental work with sweetpotatoes by the agronomy division of the North Carolina Agricultural Experiment Station and the soil fertility division of the Bureau of Chemistry and Soils of the United States Department of Agriculture.

Experiments were planned by which to study the effect on the growth of young plants and yields of sweetpotatoes on some of the principal soil types used for sweetpotato growing, of (1) various fertilizer analyses or ratios of nitrogen, phosphoric acid, and potash; (2) different quantities of fertilizers; (3) different potash sources; (4) different nitrogen sources; (5) concentrated fertilizer; and (6) fertilizer placement and time of application.

Investigations were undertaken in Carteret County with Porto Rico sweetpotatoes on Norfolk sandy loam, the prevailing soil type used for sweetpotatoes in the central coastal district of North Carolina. In 1930 [2] there were planted in this county, 2,002 acres, and 256,256 bushels of sweetpotatoes were produced, with an average yield of 128 bushels an acre.

In Craven County experiments were conducted with Porto Rico sweetpotatoes on Portsmouth fine sandy loam, a soil type occurring generally in the central coastal district of the State. In 1930, there were planted in this county, 1,377 acres, and 151,470 bushels were produced, or an average yield of 110 bushels an acre. In 1930, 18,904 acres were planted to sweetpotatoes in the central coastal district, which comprises 12 counties. Results secured in the experiments in the two counties apply generally in this district.

Fertilizer investigations with Nancy Hall sweetpotatoes were made in Catawba County on Cecil sandy loam, the prevailing soil type in the central, southern, and northern piedmont districts of the State. In this county, 1,628 acres were planted to sweetpotatoes in 1930, and 159,544 bushels, or an average yield of 98 bushels an acre, were produced. In 1930 there were planted 10,500 acres in the central piedmont district, comprising 10 counties; 8,832 acres in the southern piedmont district, comprising 11 counties; and 10,590 acres in the northern piedmont district, comprising 13 counties. The soil type chosen for these experiments is widely distributed in the piedmont section of the State, and results of the experiments on this soil have broad applications.

Fertilizer investigations with Big-Stem Jersey sweetpotatoes were started in 1925 in Currituck County on Norfolk loamy fine sand. Currituck County is in the northern coastal district of the State, and a large acreage of Norfolk loamy fine sand is used for the growing of early sweetpotatoes. In 1930, 4,663 acres were planted to sweetpotatoes in this county, and the production was 419,670 bushels, or an average yield of 90 bushels an acre. In the northern coastal district, comprising 16 counties, 15,999 acres of sweetpotatoes were planted in 1929. However, Norfolk loamy fine sand is not found generally in this district. The largest areas are in lower Currituck County, where a large sweetpotato industry has developed.

[2] Figures on sweetpotato production by counties and districts in North Carolina are from the cooperating crop-reporting service of the North Carolina Department of Agriculture and the United States Department of Agriculture.

FERTILIZER RATIO EXPERIMENTS

PLAN OF EXPERIMENTS

The fertilizer mixtures used in the fertilizer ratio experiments are those shown as bags of fertilizer in Figure 1, and charted on the triangle shown in Figure 2. In this scheme of studying fertilizer ratios, 21 different treatments of single fertilizer elements and combinations of two and three elements are used. The plan consists of using the fertilizer constituents, nitrogen, phosphoric acid, and potash, singly, two together, and three together, the ratios varying in 3 per cent

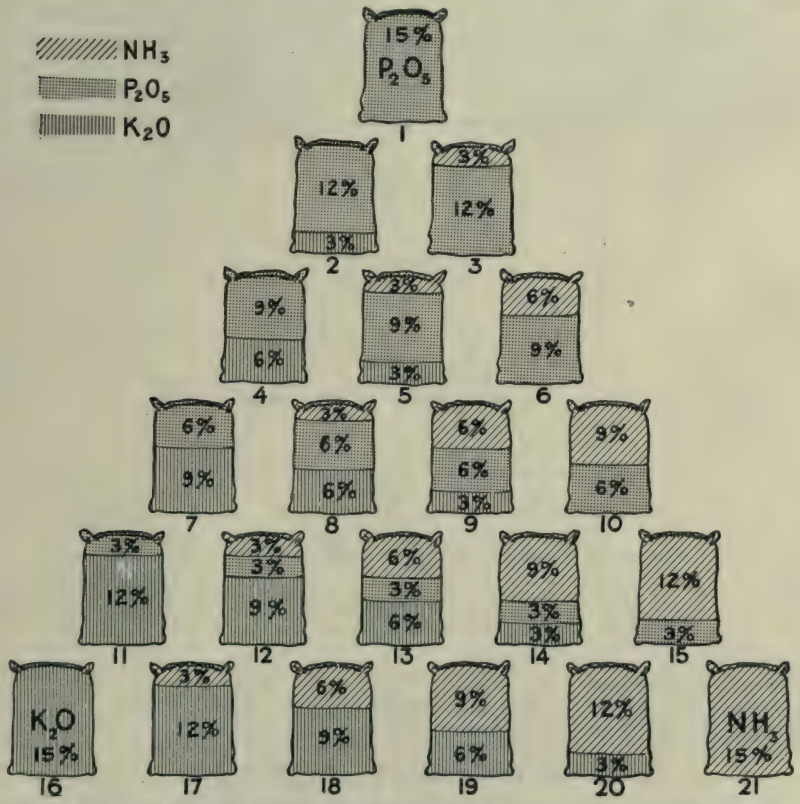


FIGURE 1.—Bags of fertilizers arranged in a triangle, showing percentages of each fertilizer ingredient in the 21 fertilizers used in the sweetpotato experiments

stages. The fertilizers represented by the points at the three angles of the triangle (fig. 2) are single constituents—ammonia, phosphoric acid, and potash. The points on the base of the triangle represent mixtures containing no phosphoric acid; those on the line just above contain 3 per cent phosphoric acid. This progression continues so that the extreme point of the triangle represents a 15 per cent phosphoric acid fertilizer. In the same manner the points on the two sides contain no potash and no nitrogen, and those on the lines parallel to the sides contain from 3 to 15 per cent of these elements.

The fertilizer constituents in each fertilizer total 15 per cent, whether 1, 2, or 3 of the constituents are present. Each plot received

the same number of pounds of plant-food constituents but in different ratios. The ratio of ammonia, phosphoric acid, and potash in each fertilizer is given in Figure 2.[3] The phosphoric acid used in the fertilizer mixtures was derived from superphosphate; the nitrogen from one-third each of sodium nitrate, ammonium sulphate, and cottonseed meal; and the potash from sulphate of potash. All the fertilizer was applied in the furrows and covered about one week before the plants were set. These experiments were planned and conducted to study the effects of different fertilizer ratios on the growth and yield of sweetpotatoes on some of the principal soil types utilized for the production of this crop in North Carolina.

The triangle plan (*15*) of fertilizer experimentation has been used extensively in field investigations, first in a grass experiment (*10*) at the Pennsylvania State College and later with many crops in various sections of the United States. This plan of preparing mixtures proved very useful in fertilizer investigations with cotton and potatoes in

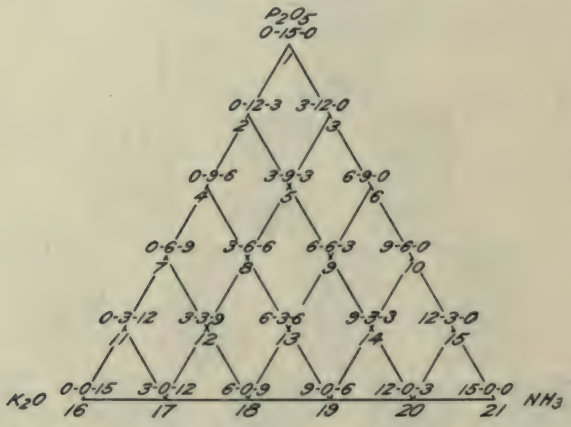


FIGURE 2.—The triangle diagram with numbered points, showing the ratios of ammonia, phosphoric acid, and potash of the 21 fertilizers in the triangle system used in the sweetpotato experiments

North Carolina (*11*) and with cotton in Georgia (*1*). It was used in sweetpotato studies by Schermerhorn in New Jersey (*14*) and Zimmerley (*20*) in Virginia.

SOIL TYPES AND RESULTS OBTAINED

The soil types on which experiments were made in each case are representative of a large area used for growing sweetpotatoes in the State. One-twentieth-acre plots were used for each fertilizer mixture, and check, or no-fertilizer, plots were distributed throughout the series.

The yield data secured in the experiments[4] on the soil types enumerated are given in Table 1 and in Figures 3, 5, 6, and 7. The stand-

[3] Fertilizer constituents are given in this bulletin in the order—ammonia, phosphoric acid, and potash. The fertilizer analyses or ratio are on the ammonia basis as this was common practice when the experiments were in operation.

[4] Assistance and cooperation of T. B. Elliott, county agent of Currituck County; A. H. Harris, former county agent of Carteret County; and J. W. Hendricks, former county agent of Catawba County, in conducting these experiments and in offering helpful suggestions is acknowledged. Credit is due F. R. Reid, Bureau of Chemistry and Soils, and S. K. Jackson and A. S. Cline, former assistant agronomists of the North Carolina Experiment Station, for assistance in obtaining the field data; and to A. R. Anthony, W. S. Boswood, C. G. Gaskell, R. L. Griggs, H. E. Patten, Clyde Mathias, and G. E. Rockett, cooperating growers who furnished land and labor for the experiments.

ard bushel of sweetpotatoes weighs 50 pounds. The fertilizer mixtures, with corresponding yields, are arranged according to their content of ammonia, phosphoric acid, and potash in Tables 2 and 3. These data are discussed for each soil type.

TABLE 1.—*Acre yields of sweetpotatoes* [1] *from fertilizers* [2] *with varying ratios of ammonia, phosphoric acid, and potash on several soil types in North Carolina*

Fertilizer No.	Fertilizer ratio NH_3–P_2O_5–K_2O	Norfolk sandy loam, Carteret County, C. G. Gaskell farm, 1924	Portsmouth fine sandy loam, Craven County, H. E. Patten farm		Cecil sandy loam, Catawba County			Norfolk loamy fine sand, Currituck County		
					G. E. Rockett farm, 1926	A. R. Anthony farm		Clyde Mathias farm, 1925	R. L. Griggs farm	
			1922	1923		1927	1928		1926	1927
		Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
X	Check.	90	60		69					
1	0–15–0	186	79	56	44	173	240	98	111	71
2	0–12–3	237	95	67	72	175	242	122	107	86
3	3–12–0	212	82	58	71	175	231	170	99	107
X	Check.		60	43		128	197	102	34	50
4	0–9–6	248	117	58	112	148	239	140	103	81
5	3–9–3	248	124	61	96	176	241	171	99	131
6	6–9–0	173	121	67	84	179	237	132	107	113
X	Check.	88	39	48	75					
7	0–6–9	242	101	69	97	188	225	134	113	89
8	3–6–6	246	150	64	139	189	268	177	132	130
9	6–6–3	186	120	62	102	177	255	171	87	128
X	Check.		73	41		146	196	98	39	53
10	9–6–0	166	101	67	71	179	236	159	73	109
11	0–3–12	224	102	65	79	174	269	165	110	77
12	3–3–9	266	157	76	116	191	281	231	115	109
X	Check.	80	52	44	66					
13	6–3–6	253	90	81	115	196	205	223	128	106
14	9–3–3	253	79	65	100	172	229	144	62	91
15	12–3–0	203	69	55	73	150	230	126	44	112
X	Check.		63	38		112	186	108	36	45
16	0–0–15	259	91	67	90	159	255	96	89	65
17	3–0–12	291	112	64	90	180	256	156	69	123
18	6–0–9	331	132	67	81	165	228	174	57	121
X	Check.	95	63	39	82	130	185	92	27	44
19	9–0–6	180	121	67	95	171	185	150	40	91
20	12–0–3	183	88	55	94	153	175	93	33	115
21	15–0–0	169	84	58	72	157	132	96	26	86
X	Check.	85	61	35						
Average of checks		87.6	58.8	41.1	73	129	191	100	34	48

[1] Sweetpotatoes were set in June and dug in November in Carteret, Craven, and Catawba Counties; set in April and dug in August in Currituck County.

[2] Source of fertilizer ingredients: Phosphoric acid from superphosphate, nitrogen one-third each from sodium nitrate, ammonium sulphate, and cottonseed meal; potash from sulphate of potash. Fertilizer applied at rate of 750 pounds per acre in Carteret, Craven, and Catawba Counties; 1,400 pounds per acre in 1925 and 1,800 pounds in 1926 and 1927 in Currituck County experiments.

TABLE 2.—*Effect of percentages of ammonia, phosphoric acid, and potash in fertilizer, on yield of sweetpotatoes on several soil types in North Carolina*

Fertilizer mixture No.[1]	Fertilizer mixtures containing 9 to 15 per cent of—	Average yield per acre on—								
		Norfolk sandy loam, Carteret County, 1924	Portsmouth fine sandy loam, Craven County		Cecil sandy loam, Catawba County			Norfolk loamy fine sand, Currituck County		
			1922	1923	1926	1927	1928	1925	1926	1927
		Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
10, 14, 15, 19, 20, 21	Ammonia	192	90	61	84	164	198	128	46	101
1, 2, 3, 4, 5, 6	Phosphoric acid.	217	103	61	80	172	238	139	104	98
7, 11, 12, 16, 17, 18	Potash	269	116	68	92	176	252	159	92	97

[1] Fertilizer mixtures as listed in Table 1 and Figures 3, 5, 6, and 7.

TABLE 3.—*Effect of different proportions of ammonia, phosphoric acid, and potash in fertilizers on yield of sweetpotatoes on several soil types in North Carolina*

Fertilizer mixture No.[1]	Fertilizer constituent in mixtures	Average yield per acre on—								
		Norfolk sandy loam, Carteret County,	Portsmouth fine sandy loam, Craven County		Cecil sandy loam, Catawba County			Norfolk loamy fine sand, Currituck County		
		1924	1922	1923	1926	1927	1928	1925	1926	1927
	Per cent	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
AMMONIA GROUP										
1, 2, 4, 7, 11, 16	0	233	98	64	82	170	245	126	105	78
3, 5, 8, 12, 17	3	253	125	65	102	182	255	181	102	120
6, 9, 13, 18	6	236	116	69	96	179	231	175	95	117
10, 14, 19	9	200	100	67	88	174	217	151	58	97
15,20	12	192	78	55	83	152	203	109	39	113
21	15	169	84	58	72	157	132	96	26	86
PHOSPHORIC ACID GROUP										
16, 17, 18, 19, 20, 21	0	235	105	63	87	164	205	127	52	100
11, 12, 13, 14, 15	3	239	99	68	97	177	243	178	91	99
7, 8, 9, 10	6	210	118	66	102	183	246	160	101	114
4, 5, 6	9	223	121	62	97	167	239	148	103	108
2, 3	12	224	88	62	72	177	236	146	103	96
1	15	186	79	56	44	173	240	98	111	71
POTASH GROUP										
1, 3, 6, 10, 15, 21	0	185	89	60	69	169	218	130	77	100
2, 5, 9, 14, 20	3	221	101	62	93	171	228	140	77	110
4, 8, 13, 19	6	232	119	68	115	176	224	172	101	102
7, 12, 18	9	280	130	71	98	181	245	180	95	106
11, 17	12	257	107	65	85	177	263	160	89	100
16	15	259	91	67	90	159	255	96	89	65

[1] Fertilizer mixtures as listed in Table 1 and Figures 3, 5, 6, and 7.

NORFOLK SANDY LOAM

The experiments on Norfolk sandy loam were made in 1924 on the farm of C. G. Gaskill, in Carteret County, east of Beaufort. Porto Rico sweetpotatoes were set in June and dug in November. Fertilizers were applied at the rate of 750 pounds an acre in the furrows and covered one week before the plants were set. The yield data given in Table 1 are charted on the triangle diagram in Figure 3. The results can be better understood by a study of the data given in the figure.

Comparing the single-element fertilizers, potash (fertilizer No. 16) gave a larger yield than did phosphoric acid (fertilizer No. 1) or ammonia (fertilizer 21). This greater response from potash is in keeping with the higher yields obtained from the complete fertilizers containing high percentages of potash, as compared with yields from complete fertilizers containing high percentages of phosphoric acid or high percentages of ammonia. These comparative data are shown for the Norfolk sandy loam in Table 2. The fertilizers containing high percentages of potash are those in Figure 3, included in the subtriangle outlined by mixtures 7, 16, and 18. The fertilizers containing high percentages of phosphoric acid are within the subtriangle formed by

Nos. 1, 4, and 6, and the fertilizers containing high percentages of ammonia are in the subtriangle outlined by Nos. 10, 19, and 21.

The three mixtures producing highest yields are Nos. 12, 17, and 18. These mixtures contain ratios of ammonia, phosphoric acid, and potash as follows: 3–3–9, 3–0–12, and 6–0–9, and the average composition of the three mixtures is 4–1–10. This ratio is charted in the small triangle formed by these three mixtures in Figure 3.

The fertilizer mixtures shown in Figure 3 are arranged in Table 3 according to the amount of ammonia, phosphoric acid, and potash they contain, and the average yield of each group is tabulated.

The fertilizer mixtures containing 3 per cent of ammonia have given the largest average yields of the varying-nitrogen group. The yields decrease as the nitrogen in the fertilizer mixtures increases above this percentage. There is no correlation between yield and the phosphoric acid content of the fertilizer, but there is a correlation between yield and potash content, the yield increasing with increase of potash in the fertilizer up to 9 per cent. Fertilizers having percentages of potash

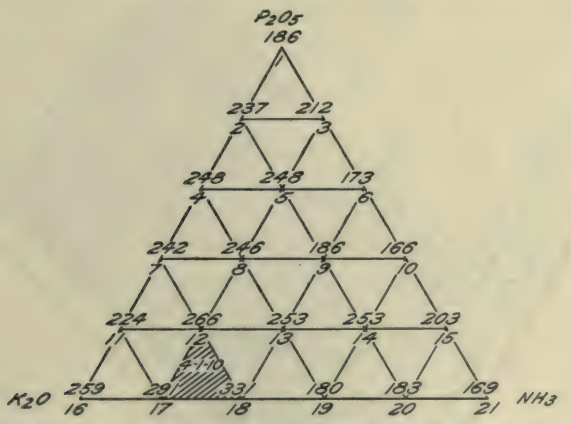


FIGURE 3.—Yield of sweetpotatoes in bushels per acre from fertilizers containing various ratios of ammonia, phosphoric acid, and potash on Norfolk sandy loam in Carteret County, N. C., 1924

higher than this gave lower yields. This compilation of the data shows that the largest yields are obtained with mixtures containing 3 per cent ammonia, no phosphoric acid, and 9 per cent potash. This fertilizer analysis does not differ widely from that derived by averaging the composition of the three mixtures giving highest yields. This average composition is 4 per cent ammonia, 1 per cent phosphoric acid, and 10 per cent potash. From these data it would seem that a fertilizer containing 3 to 4 per cent ammonia, 0 to 1 per cent phosphoric acid, and 9 to 10 per cent potash should give good results on this soil. The data as a whole seem to show that these percentages of nitrogen and potash are the best in a mixture used at the rate of 750 pounds an acre. The phosphoric acid effect is not altogether uniform in the various mixtures.

PORTSMOUTH FINE SANDY LOAM

The experiments on Portsmouth fine sandy loam were made on the farm of H. E. Patten, near New Bern, Craven County, in 1922 and

repeated on an adjoining field in 1923. A soil map of the field showing the layout of the experimental plots is shown in Figure 4. Porto Rico sweetpotatoes were set in June and dug in November. The fertilizers were applied at the rate of 750 pounds an acre. In the plots containing high percentages of ammonia, Nos. 15, 20, and 21, difficulty in maintaining a stand was experienced. Some of the plants died shortly after being set, and it was necessary to reset the plots in which this occurred. The yield data are given in Table 1 and in Figure 5.

In the 2-year experiments the yields from potash (fertilizer No. 16) were higher than from phosphoric acid (fertilizer No. 1) or from am-

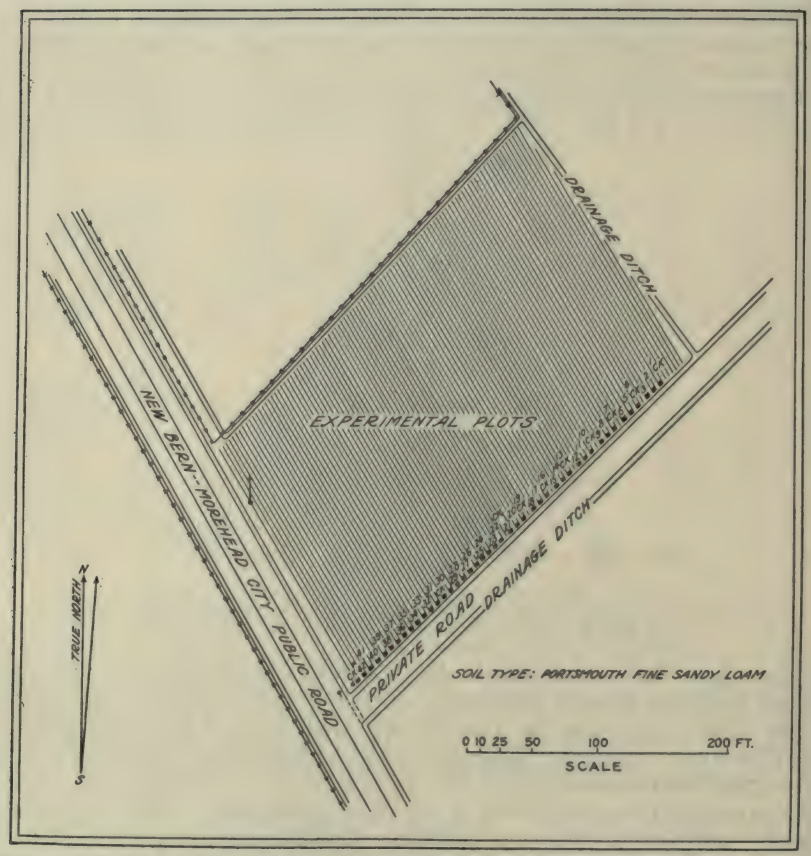


FIGURE 4.—Map of experiment field on Portsmouth fine sandy loam in New Bern, Craven County, N. C., 1923

monia (fertilizer No. 21). This result is in harmony with the higher yields produced by the mixtures containing high percentages of potash as compared with yields produced by the mixtures containing high percentages of phosphoric acid and the mixtures containing high percentages of ammonia. The average yields of these three groups are given in Table 2. The three fertilizers giving the highest yields in 1922 (fig. 5, A) are Nos. 8, 12, and 18. These form an inner triangle shown in the shaded area. The ratio of ammonia, phosphoric acid,

and potash of these three mixtures is, respectively, 3–6–6, 3–3–9, and 6–0–9. Two of these mixtures contain 3 per cent ammonia, and two contain 9 per cent potash. The average analysis of the three fertilizers is 4 per cent ammonia, 3 per cent phosphoric acid, and 8 per cent potash. The three fertilizers producing highest yields in 1923 (fig. 5, B) are Nos. 7, 12, and 13, having the following respective ratios of ammonia, phosphoric acid, and potash: 0–6–9, 3–3–9, and 6–3–6, averaging 3–4–8. This compilation of the 2-year data would indicate

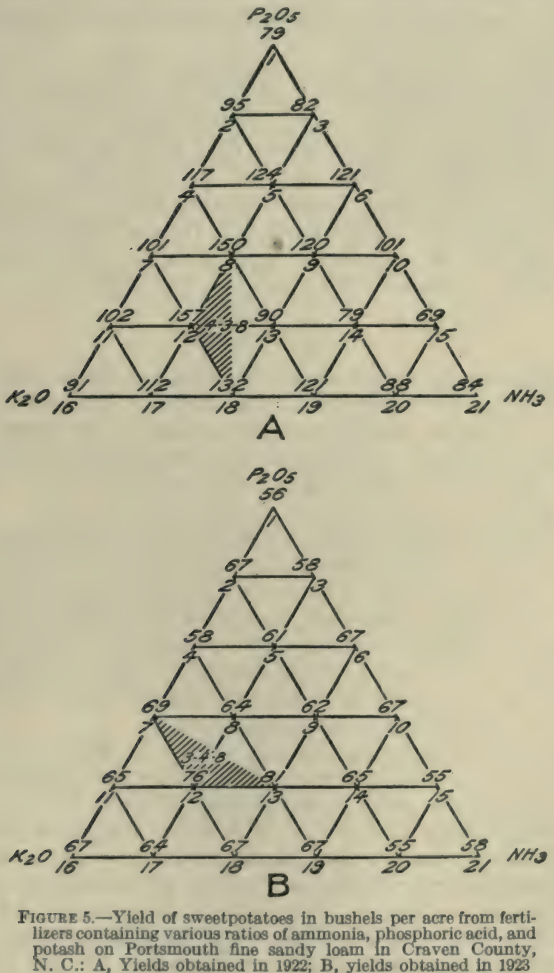


FIGURE 5.—Yield of sweetpotatoes in bushels per acre from fertilizers containing various ratios of ammonia, phosphoric acid, and potash on Portsmouth fine sandy loam in Craven County, N. C.: A, Yields obtained in 1922; B, yields obtained in 1923

that a fertilizer for sweetpotatoes on this soil should contain 3 to 4 per cent ammonia, 3 to 4 per cent phosphoric acid, and 8 to 9 per cent potash.

When the yield data from the fertilizers represented by points along each line of the triangle, that is, according to the percentage of ammonia, phosphoric acid, or potash in the fertilizer, are considered, the result is interesting and in harmony with the deduction discussed

in the preceding paragraph. In Table 3 the average yields for fertilizers containing increasing quantities of ammonia, phosphoric acid, or potash are given. In 1922 the mixtures containing 3 per cent ammonia gave highest average yields of the varying ammonia groups. The yields decreased with increasing percentages of ammonia above 3 per cent. The result in 1923 was somewhat similar, except the largest average yield was obtained from the 6 per cent ammonia group; however, the average yields for the no-ammonia and 3, 6, and 9 per cent ammonia groups do not vary widely. In the phosphoric acid groups there is not a close correlation between yields and phosphoric acid content of the fertilizer.

The mixtures containing 9 per cent potash gave the largest yields of the varying potash groups in each year's experiments. There is an increase in yields with increasing percentages of potash up to this amount. Higher percentages than this gave smaller yields. This compilation of the data indicates that the most effective fertilizer for sweetpotatoes on this type of soil contains about 3 per cent ammonia and 9 per cent potash. This does not vary widely from the former deduction, so far as ammonia and potash are concerned. The phosphoric acid correlation with yield is not clear.

CECIL SANDY LOAM

The experiments on Cecil sandy loam were made near Newton in Catawba County, in 1926, 1927, and 1928. The first was on the farm of G. E. Rockett and the others on soil of the same type on the farm of A. R. Anthony. Nancy Hall sweetpotatoes were set in June and dug in October. Fertilizers were applied at the rate of 750 pounds an acre a few days before the plants were set.

The yield data given in Table 1 are charted on triangle diagrams in Figure 6. Potash used alone gave a higher yield than did phosphate alone or ammonia alone in 1926 and 1928, but phosphate was highest in 1927. However, when the group of mixtures containing high percentages of potash is compared to the group containing high percentages of phosphoric acid or the group containing high percentages of ammonia, as compiled in Table 2, the average yields from the potash group are highest in each experiment.

The three mixtures giving highest yields in the first two years are Nos. 8, 12, and 13, which contain the following respective ratios of ammonia, phosphoric acid, and potash: 3–6–6, 3–3–9, and 6–3–6, with an average ratio of 4–4–7. The three mixtures giving highest yields in the third year are Nos. 8, 11, and 12. The average ratio of ammonia, phosphoric acid, and potash, of the three mixtures producing highest yields, is 2–4–9. The points represented by these three mixtures form an inner triangle, shown in the shaded areas in Figure 6.

When the data are considered with respect to the percentage of ammonia, phosphoric acid, or potash in the mixtures, as compiled in Table 3, it is seen that fertilizers containing 3 per cent of ammonia gave highest average yields in the nitrogen group each year. In the varying phosphoric acid groups the mixtures containing 6 per cent phosphoric acid gave the highest yields each year. In the potash group the highest yields were obtained from mixtures containing 6 per cent potash in 1926, 9 per cent in 1927, and 12 per cent in 1928.

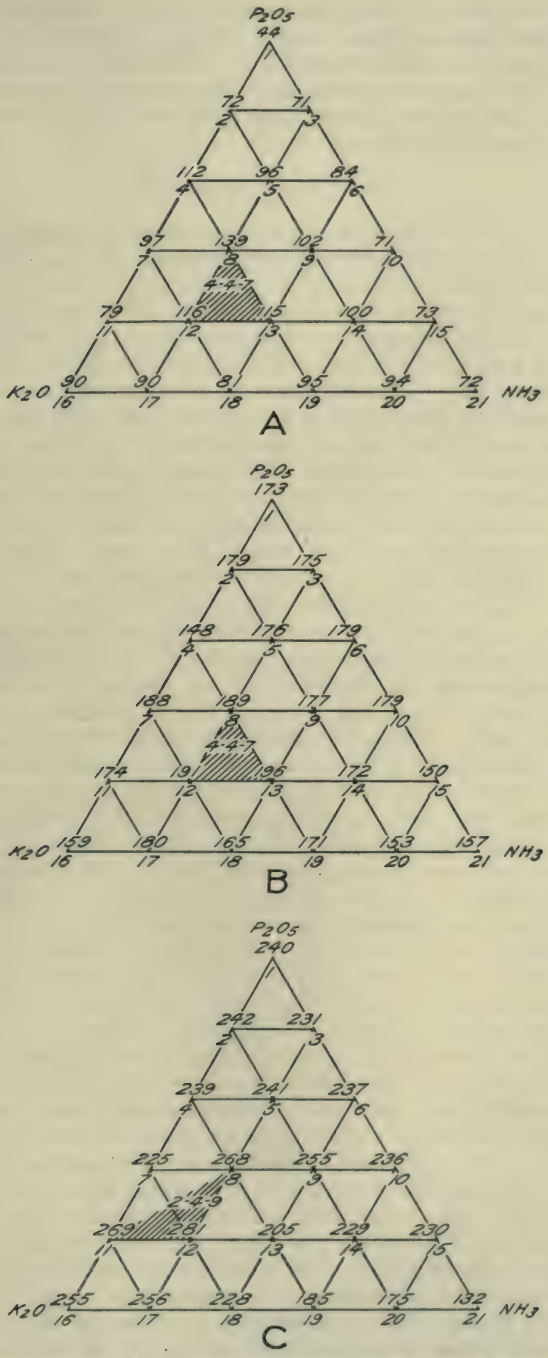


FIGURE 6.—Yield of sweetpotatoes in bushels per acre from fertilizers containing various ratios of ammonia, phosphoric acid, and potash on Cecil sandy loam in Catawba County, N. C.: A, Yields obtained in 1926; B, yields obtained in 1927; C, yields obtained in 1928

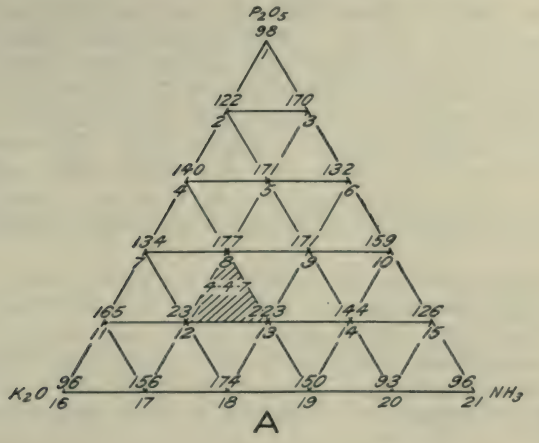
From all the data it is apparent that potash is important in fertilizing sweetpotatoes on Cecil sandy loam. Nitrogen appears to be needed, but only in small quantities. The effect of phosphoric acid is variable. It is apparent that a mixture containing 2 to 4 per cent ammonia, 4 to 6 per cent phosphoric acid, and 7 to 9 per cent potash should be selected for this soil.

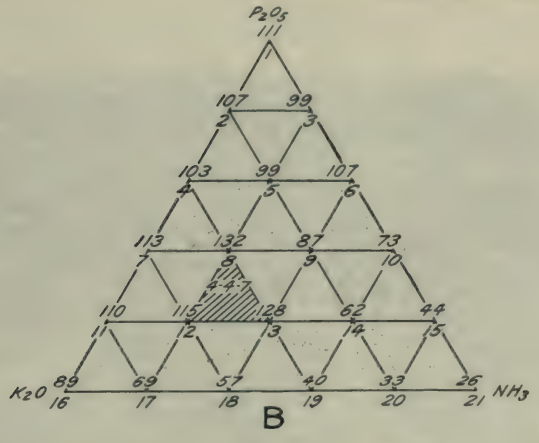
NORFOLK LOAMY FINE SAND

The experiments on Norfolk loamy fine sand were made in Currituck County in 1925, 1926, and 1927, the first on the farm of Clyde Mathias, and the two later on the farm of R. L. Griggs. The soil conditions on the two farms where the experiments were made are similar and are typical of the Norfolk loamy fine sand occurring in Currituck County. The fertilizer was applied under the plant row about 10 days before the plants were set. It was mixed in the soil and covered by two furrows. Fertilizer was applied at the rate of 1,400 pounds an acre the first year and 1,800 pounds the following two years. Big-Stem Jersey sweetpotatoes were set in April and dug in August.

In the experiments conducted during 1926 and 1927 considerable difficulty was experienced in maintaining a stand of plants. On the plots which received fertilizer containing more than 6 per cent ammonia, there was only 75 to 85 per cent of a stand. Many of the plants in the high-nitrogen plots died within the first two weeks after they were set. About 30 per cent of the plants died in plot 21 which received a 15 per cent ammonia fertilizer. It was noted that the stand of sweetpotato plants was best on the no-fertilizer plots and those plots (Nos. 1, 2, 4, 7, 11, and 16) where fertilizers containing no nitrogen were used. The plots receiving fertilizers containing a high proportion of potash or a high proportion of phosphoric acid had relatively good stands. The season was extremely dry from the time the plants were set until they were dug, which undoubtedly accentuated the fertilizer injury to the young plants. Better stands of sweetpotato plants might have been obtained had the fertilizers containing the higher percentages of ammonia been applied partly before planting and partly as a side application several weeks later.

The yield data for the three years are given in Table 1 and in Figure 7. The Norfolk loamy fine sand in Currituck County is a loose light sand, deficient in plant food. The effect of fertilizers on the growth of sweetpotato vines is shown in Figure 8. Large quantities of commercial fertilizer are required for successful sweetpotato production. This is indicated by the yields from the no-fertilizer plots. The sweetpotatoes dug from the check plots were small and hardly suitable for market as compared with the large prime potatoes produced on the fertilizer plots. Although there is a large increase in yield on most of the complete-fertilizer plots, it is noted that most of the high-nitrogen fertilizer plots produced scarcely as much as the no-fertilizer plots. This is probably due to the fact that many of the sweetpotato plants died or were badly stunted while young and that the surviving plants developed an abundance of vegetation. Small yields were obtained with phosphoric acid, potash, or nitrogen alone. All three fertilizer constituents are apparently necessary for sweetpotatoes on this soil.





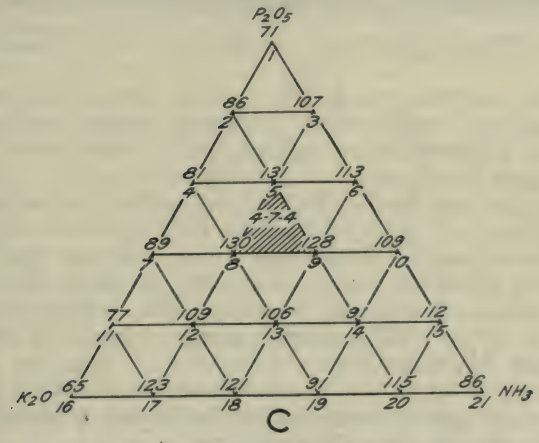


FIGURE 7.—Yield of sweetpotatoes in bushels per acre from fertilizers containing various ratios of ammonia, phosphoric acid, and potash on Norfolk loamy fine sand in Currituck County, N. C.: A, Yields obtained in 1925; B, yields obtained in 1926; C, yields obtained in 1927

In 1925 and 1926 the three fertilizer mixtures producing the highest yields were Nos. 8, 12, and 13. (Fig. 7, A and B.) These have ratios of ammonia, phosphoric acid, and potash, respectively, of 3–6–6, 3–3–9, and 6–3–6, with an average of 4–4–7. In 1927 the three mixtures giving the highest yields were Nos. 5, 8, and 9, as charted in the small inner shaded triangle in Figure 7, C. The composition of these three mixtures in ammonia, phosphoric acid, and potash is, respectively, 3–9–3, 3–6–6, and 6–6–3, with an average of 4–7–4. This result is considerably at variance with that obtained the first two years.

The data are interesting in respect to the yields from the fertilizers containing high percentages of ammonia, high percentages of phosphoric acid, and high percentages of potash as given in Table 2. In 1925 the average yields from the mixtures containing high percentages of potash were greater than the average yields from mixtures containing high percentages of ammonia or high percentages of phos-

FIGURE 8.—Effect of fertilizers on growth of sweetpotato vines on Norfolk loamy fine sand: A, Fertilizer analysis, 3-6-6; B, fertilizer analysis, 6-3-6; C, no fertilizer

phoric acid. In 1926 the average yields from mixtures containing high percentages of phosphoric acid were higher and in 1927 yields from the three groups were similar, with yields from the mixtures containing high percentages of ammonia leading.

The data are compiled in Table 3, according to the percentages of ammonia, phosphoric acid, and potash the mixtures contain. In 1925 the mixtures containing 3 per cent ammonia gave the largest yields of the varying ammonia groups. In 1926, however, the mixtures containing no ammonia gave the highest yields, which were closely followed by the 3 per cent ammonia group. Again in 1927 the 3 per cent ammonia fertilizers led.

There seems to have been no consistent correlation between yield and phosphoric acid content of the fertilizers, although the results indicate that phosphoric acid is required.

Considering the varying potash fertilizers, the largest average yields of sweetpotatoes were produced in 1925 with the 9 per cent potash

mixtures, in 1926 with the 6 per cent potash mixtures, and in 1927 with the 3 per cent potash mixtures.

Judging by this compilation of data the best fertilizer analysis for this soil would be a mixture containing about 3 per cent ammonia, 3 to 6 per cent phosphoric acid, and 6 to 9 per cent potash. This deduction does not differ widely from the 4–4–7 ratio derived by averaging the composition of the three mixtures producing the highest yields.

The results obtained in each of the three years' experiments are not in close harmony, and to further study the influence of potash on Norfolk loamy fine sand another experiment was made on the Griggs farm in 1928. The results are given in Table 4.

TABLE 4.—*Effect of fertilizer* [1] *containing varying percentages of potash on yield of sweetpotatoes on Norfolk loamy fine sand, 1928*

Fertilizer analysis			Yield per acre
NH_3	P_2O_5	K_2O	
Per cent	*Per cent*	*Per cent*	*Bushels*
4	8	0	104
4	8	4	128
4	8	6	144
4	8	8	175
4	8	10	166
4	8	12	162
0	0	0	[2] 56

[1] Nitrogen in fertilizer derived equally from sodium nitrate and cottonseed meal, phosphoric acid from superphosphate, and potash from sulphate of potash. Fertilizer applied at rate of 1,400 pounds an acre.
[2] Small, nonmarketable sweetpotatoes.

In the 1928 experiment the yields increased with an increase of potash up to 8 per cent in the mixture. There was a slight decrease with increase of potash above 8 per cent.

DISCUSSION

The results of experiments reported in the foregoing pages are rather consistent in showing that relatively small percentages of nitrogen in fertilizers are required for best results on the soils used in the sweetpotato experiments in North Carolina. The data are also consistent in showing that relatively high percentages of potash are required for best results on these soils. Phosphate appears to be needed, especially on the thin, loose, sandy soils of the northern coastal-plain section of the State, but there is no close correlation of the phosphoric acid content of the fertilizer with the yield of sweetpotatoes.

The fertilizer requirements of Norfolk sandy loam, Portsmouth fine sandy loam, Cecil sandy loam, and Norfolk loamy fine sand, for sweetpotatoes, do not differ widely. In most of the experiments the largest yields were obtained with fertilizers containing 3 to 6 per cent ammonia, a moderate percentage of phosphoric acid, and 8 to 10 per cent potash. From consideration of all the data it is concluded that the best fertilizer for sweetpotatoes is one containing 3 to 4 per cent ammonia, about 6 per cent phosphoric acid, and 8 to 10 per cent potash. The 4–8–8, 3–8–8, 3–8–10, and 4–8–10 mixtures are generally used for sweetpotatoes in North Carolina on the soils discussed above.

The results of the experiments reported in this bulletin, so far as yield is concerned, indicate that a ratio lower than 8 per cent phosphoric acid to 4 per cent of ammonia and 8 per cent of potash is most effective. The experiments were made on soils which in previous years had been liberally supplied with fertilizers containing high percentages of phosphoric acid, and the soils no doubt contained considerable residual phosphate. The effect of phosphoric acid on most of the soils was variable, and it was not indicated that large percentages were essential in growing sweetpotatoes so far as the yield alone is concerned. For virgin soils and soils previously tilled to crops on which no, or very little, phosphoric-acid fertilizer was used, a fertilizer for sweetpotatoes should probably contain 8 per cent phosphoric acid with 4 per cent ammonia and 8 per cent potash. A sufficient supply of available phosphoric acid is necessary for sweetpotatoes grown on thin sandy soils if they are to develop strong, stocky plants which can withstand unfavorable weather conditions in early spring.

The results of fertilizer experiments on other soil types in various sections of the United States are of interest in connection with these studies. Results of a fertilizer-ratio experiment, in which Big-Stem Jersey sweetpotatoes were grown on Sassafras sandy loam on the Eastern Shore branch of the Virginia Truck Experiment Station (*7*, *20*) were reported in 1929. A fertilizer high in potash, with low phosphoric acid and nitrogen plant-food ratios proved most effective. There was a uniform rise in yield coincident with increases in the potash content up to 15 per cent. There was a downward trend when the nitrogen was increased beyond 6 per cent. A 3–3–15 mixture gave the largest yields and the best quality of potatoes on the Sassafras sandy loam.

Schermerhorn (*13*, *14*) conducted fertilizer-ratio experiments with Yellow Jersey sweetpotatoes on coarse sandy soils in southern New Jersey and found that a 3-8-8 mixture gave best results. Under average conditions an application ranging from 1,000 to 1,500 pounds of fertilizer per acre was most economical. Fertilizers containing more than 8 per cent of potash were not profitable. Organic nitrogen of vegetable and animal origin was superior to mineral nitrogen, but, owing to the cost of organic nitrogen, it is recommended that for sweetpotato fertilizers the nitrogen be derived one-half from mineral sources and one-half from organic sources. Former work (*19*) conducted at the New Jersey station had shown that kainit was detrimental to sweetpotatoes, not, perhaps, because of the form of potash, but because of the very large quantity of salt necessarily applied in order to obtain the desired quantity of potash. Potassium chloride gave slightly better results than potassium sulphate. It is pointed out that nitrogen and potassium influence the shape and size of sweetpotatoes.

Experiments with Big-Stem Jersey sweetpotatoes on the western and eastern shores of Chesapeake Bay, in Maryland, on Norfolk sand and Sassafras loam, made by Geise (*3*, *4*) show a need for fertilizers containing high percentages of potash. A 2–8–10 fertilizer gave an increase over a 2–8–8 mixture, and the yield from a 3–8–10 exceeded that from a 3–8–8 mixture. Houghland (*6*) also found that Big-Stem Jersey sweetpotatoes responded to potash fertilizers on Norfolk sandy loam in Maryland.

The fertilizer requirements of Triumph sweetpotatoes on Florida sand were studied by Scott (*16*). He found that nitrogen, phosphoric acid, and potash were required. The omission of potash resulted in depressed yields. Potassium chloride gave somewhat better results than potassium sulphate. Stuckey (*17*) of the Georgia Agricultural Experiment Station, has reported results of fertilizer experiments with Pumpkin (yam) sweetpotatoes made on Cecil clay loam in which larger yields resulted from the application of potassium sulphate than from applying nitrogen or superphosphate. A mixture containing all three of these fertilizer constituents gave larger yields than any one material.

From the results obtained in these experiments it would seem that the coastal-plain soils bordering the Atlantic seaboard appear to need a complete fertilizer for the successful production of sweetpotatoes. A high ratio of potash to nitrogen and phosphorus is apparently required for best results. Results of experiments on the coastal-plain soils in New Jersey, Maryland, Virginia, North Carolina, and Florida are generally in harmony in that they show that best results may be obtained with fertilizers containing a comparatively low percentage of nitrogen and phosphoric acid and a high percentage of potash. On most of the coastal-plain soils the experiments apparently indicate a fertilizer of 3 to 4 per cent nitrogen, 4 to 8 per cent phosphoric acid, and 8 to 10 per cent potash for best results with sweetpotatoes, although on some of the soils the need for fertilizer containing a higher percentage of potash is indicated.

In southern Mississippi (*2*), on sandy loam soils, Porto Rico sweetpotatoes responded to fertilizers containing nitrogen, phosphoric acid, and potash. The results are somewhat similar to those obtained on the sandy loam soils of the Atlantic seaboard. Generally yields increased with the increase of potash up to 8 per cent in the fertilizer. Fertilizers containing more than 4 per cent nitrogen gave reduced yields.

Sweetpotatoes remove from the soil more potash than nitrogen and phosphorus, as shown by Keitt (*8*) in his work with a number of varieties grown on a sandy loam soil in South Carolina. Nitrogen, phosphoric acid, and potash were removed in the ratio of 31–8–61, respectively.

Soils on which sweetpotato experiments have been made in the Central and Western States appear to have a fertilizer requirement different from those already discussed. On Susquehanna fine sandy loam in eastern Texas, Hotchkiss (*5*) found that there was less response by Dooley (yam) sweetpotatoes to potash than to other fertilizer materials. Superphosphate consistently produced larger yields in these experiments. Experiments in Arkansas (*9*) with Nancy Hall and Porto Rico sweetpotatoes are reported showing good results from a 3–8–2 mixture, and negative results from the use of additional quantities of potash. Quinn (*12*) working with Porto Rico sweetpotatoes on a silt loam soil in the eastern part of northern Missouri found that only slight gains were effected by using a fertilizer containing all three constituents. The yields from the mixture were only slightly better than from potash alone.

130350°—32——3

DIFFERENT QUANTITIES OF FERTILIZERS

The results of nine experiments made on four soil types with different quantities of fertilizers are given in Table 5. In each experiment two fertilizer mixtures were used, one relatively low in potash and the other relatively high. On Portsmouth fine sandy loam and Norfolk sandy loam, mixtures analyzing 3 per cent ammonia, 7 per cent phosphoric acid, and 5 per cent potash were used. The second mixture contained the same percentages of ammonia and phosphoric acid and 10 per cent of potash. On Cecil sandy loam and Norfolk loamy fine sand, 4–8–4 and 4–8–8 mixtures were used. The phosphoric acid in the mixtures was derived from superphosphate, the nitrogen from one-half mineral and one-half organic sources, and the potash from potassium sulphate. The fertilizer was applied in the plant row, mixed in the soil, and covered by two furrows, from 10 days to 2 weeks before the plants were set.

TABLE 5.—*Results of sweetpotato experiments with different quantities of fertilizers containing low and high percentages of potash*

Soil type and location	Year	Fertilizer per acre	Yield of sweetpotatoes per acre		
			Fertilizer 3–7–5 [1]	Fertilizer 3–7–10 [1]	No fertilizer
		Pounds	*Bushels*	*Bushels*	*Bushels*
Portsmouth fine sandy loam, H. E. Patten farm, Craven County	1922	500	126	149	
		750	146	181	
		1,000	154	208	
		None.			91
	1923	500	53	70	
		750	64	78	
		1,000	76	79	
		None.			41
Norfolk sandy loam, C. G. Gaskell farm, Carteret County	1924	500	150	135	
		750	162	169	
		1,000	165	175	
		None.			89
			Fertilizer 4–8–4 [1]	Fertilizer 4–8–8 [1]	
			Bushels	*Bushels*	
Cecil sandy loam, G. E. Rockett farm, Catawba County	1925	500	54	107	
		750	65	82	
		1,000	79	94	
		None.			46
	1926	500	80	93	
		750	92	99	
		1,000	95	94	
		None.			77
Cecil sandy loam, A. R. Anthony farm, Catawba County	1927	500	148	178	
		750	166	185	
		1,000	166	189	
		None.			100
	1928	500	205	224	
		750	205	277	
		1,000	227	222	
		None.			168
Norfolk loamy fine sand, Clyde Mathias farm, Currituck County	1925	1,000	193	221	
		1,200	195	220	
		1,400	200	219	
		None.			110
Norfolk loamy fine sand, R. L. Griggs farm, Currituck County	1926	1,000	88	126	
		1,500	91	129	
		1,800	110	121	
		2,000	116	117	
		None.			34

[1] Percentages of ammonia, phosphoric acid, and potash, respectively. Fertilizer prepared from superphosphate, potassium sulphate, sodium nitrate, ammonium sulphate, and cottonseed meal.

In all except three cases the fertilizers containing the larger quantities of potash gave a larger yield than did corresponding applications of fertilizers containing less potash.

PORTSMOUTH FINE SANDY LOAM

In experiments on Portsmouth fine sandy loam the yield increased with increased quantities of fertilizers used. However, the results as a whole indicate that 750 pounds an acre is more economical than 1,000 pounds an acre. In three of the tests the yield from 1,000 pounds an acre was only slightly increased over that from 750 pounds. It is interesting that 750 pounds of 3–7–5 fertilizer produced a yield not quite so large as that from 500 pounds of 3–7–10, and that 1,000 pounds of 3–7–5 fertilizer did not produce so large a yield as did 750 pounds of 3–7–10 fertilizer. The yields of sweetpotatoes produced by different quantities of fertilizers are shown in Figure 9.

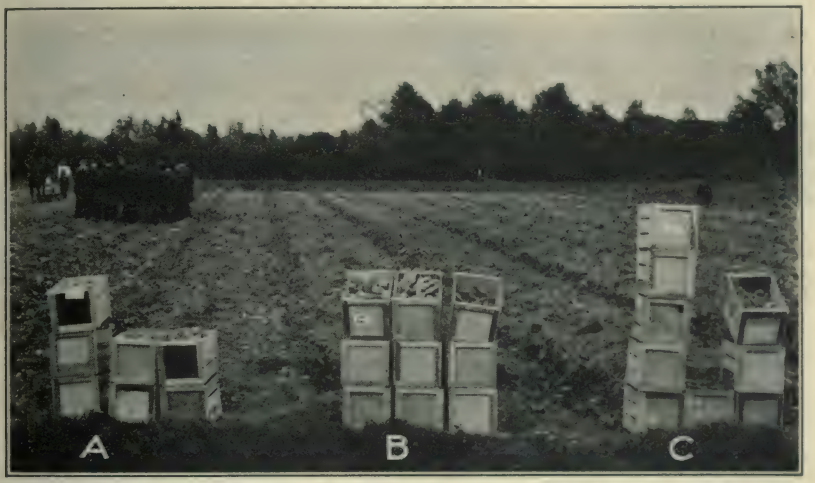


FIGURE 9.—Yield of sweetpotatoes on Portsmouth fine sandy loam from 1/20-acre plots fertilized with a mixture analyzing 3 per cent ammonia, 7 per cent phosphoric acid, and 5 per cent potash: A, With 500 pounds per acre, 3 crates of primes, 2 crates of seconds, 2 crates of culls; B, with 750 pounds per acre, 3 crates of primes, 3 crates of seconds, 3 crates of culls; C, with 1,000 pounds per acre, 5 crates of primes, 1 crate of seconds, 3 crates of culls

NORFOLK SANDY LOAM

In the experiment on Norfolk sandy loam, yields from increasing amounts of fertilizer did not vary widely. There was only a slight increase in yield from 1,000 pounds an acre over 750 pounds.

CECIL SANDY LOAM

Seven hundred and fifty pounds of fertilizer an acre gave a larger yield than 500 pounds in all the experiments except one on Cecil sandy loam. There was a slight increase in yield with 1,000 pounds over 750 pounds in four cases, but this was not true in four other cases, and the increases were not sufficiently large to justify the use of the larger quantities. In three years, 500 pounds of 4–8–8 fertilizer gave a larger yield than did 750 pounds of 4–8–4 fertilizer.

The influence of fertilizers containing various quantities of potash on yield of sweetpotatoes is shown in Figure 10.

NORFOLK LOAMY FINE SAND

In the experiments on Norfolk loamy fine sand the fertilizer applications ranged from 1,000 to 1,400 pounds an acre in 1925, and from 1,000 to 2,000 pounds in 1926. In each year 1,000 pounds of 4–8–8 fertilizer gave almost as good yields as larger quantities. However, where 4–8–4 fertilizer was used, the highest yields were obtained with 1,400 pounds an acre in 1925 and with 2,000 pounds in 1926. These were the maximum quantities used. In each case the yields from smaller quantities were nearly as large.

The yields of sweetpotatoes from different quantities of fertilizers and from no fertilizer are shown graphically in Figure 11 for each soil type used in the experiments.

NITROGEN SOURCES

To study the effect of nitrogen sources in sweetpotato fertilizers, experiments were made in which two mineral salts and two organic materials were used, each as the sole source of nitrogen in fertilizers containing superphosphate and potash. A mixture was included in which the nitrogen was derived, one-third each, from sodium nitrate, ammonium sulphate, and cottonseed meal. The results of experiments on four soil types are given in Table 6.

TABLE 6.—*Results of sweetpotato experiments with fertilizers* [1] *containing nitrogen from various sources, phosphoric acid, and potash on several soil types in North Carolina*

Soil type	Location	Year	Yield of sweetpotatoes per acre with—				
			Sodium nitrate	Ammonium sulphate	Cottonseed meal	Fish scrap	One-third from sodium nitrate, one-third from ammonium sulphate, and one-third from cottonseed meal
			Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*
Portsmouth fine sandy loam.	H. E. Patten farm, Craven County.	1922	137	.....	121	158	120
		1923	92	.....	102	100	100
Norfolk sandy loam.	C. G. Gaskell farm, Carteret County.	1924	198	.....	171	146	186
Cecil sandy loam.	G. E. Rockett farm, Catawba County.	1925	86	60	73	77	.....
		1926	88	104	116	115	122
	A. R. Anthony farm, Catawba County.	1927	170	163	189	178	181
		1928	291	293	274	263	277
Norfolk loamy fine sand.	Clyde Mathias farm, Currituck County.	1925	95	108	130	130	170
	R. L. Griggs farm, Currituck County.	1926	63	77	108	95	93
		1927	86	99	107	108	142
Average	.....	.....	130.6	.....	139.1	137	154.5

[1] Fertilizer containing 4 per cent ammonia, 8 per cent phosphoric acid, and 8 per cent potash applied at rate of 750 pounds an acre in all experiments except on Norfolk loamy fine sand, where 1,400 pounds an acre were used in 1925 and 1,800 pounds in 1926 and 1927.

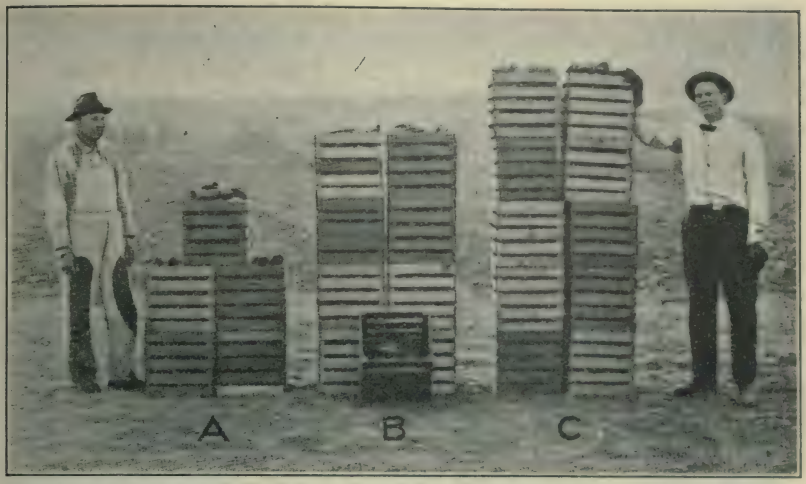


FIGURE 10.—Effect of fertilizers containing various percentages of potash on yield of sweetpotatoes on Cecil sandy loam. Yield from 1/20-acre plots: A, No fertilizer, yield equivalent to 100 bushels per acre; B, yield from 750 pounds of fertilizer containing 4 per cent ammonia, 8 per cent phosphoric acid, and 4 per cent potash, equivalent to 166 bushels per acre; C, yield from 750 pounds of fertilizer containing 4 per cent ammonia, 8 per cent phosphoric acid, and 8 per cent potash, equivalent to 185 bushels per acre

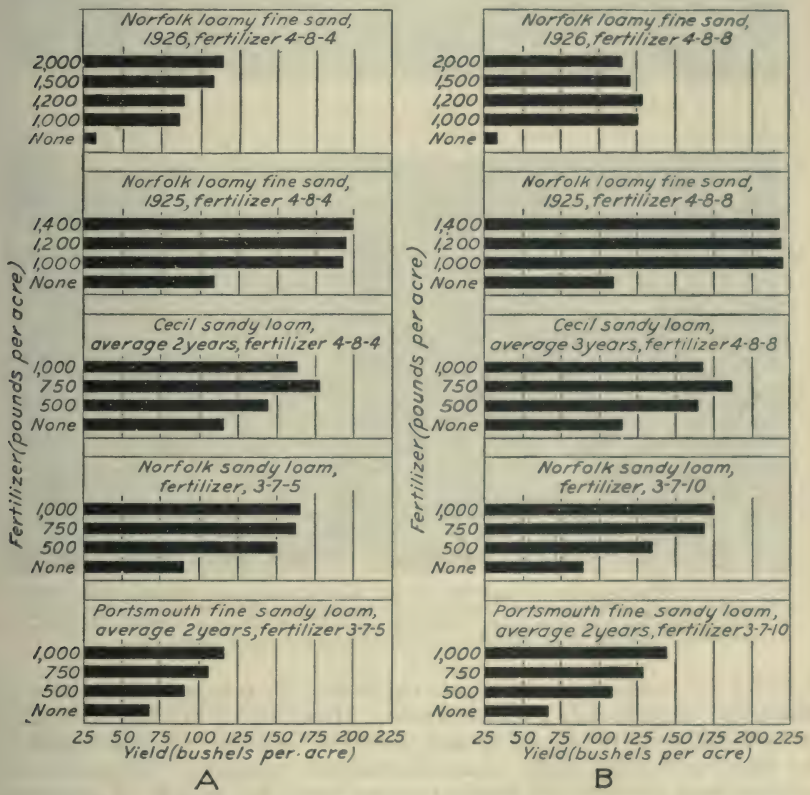


FIGURE 11.—Effect of varying quantities of several fertilizers on yield of sweetpotatoes on four soil types. A, Relatively low potash fertilizers; B, relatively high potash fertilizers

There was not a great difference in yield from the use of fertilizers containing nitrogen from various sources in the experiments on Portsmouth fine sandy loam, Norfolk sandy loam, and Cecil sandy loam. The fertilizer application was 750 pounds an acre, and no injury to young plants was noted from any of the treatments on these soils.

In the Currituck County experiments on Norfolk loamy fine sand, on which 1,400 and 1,800 pounds an acre of fertilizer were used, sodium

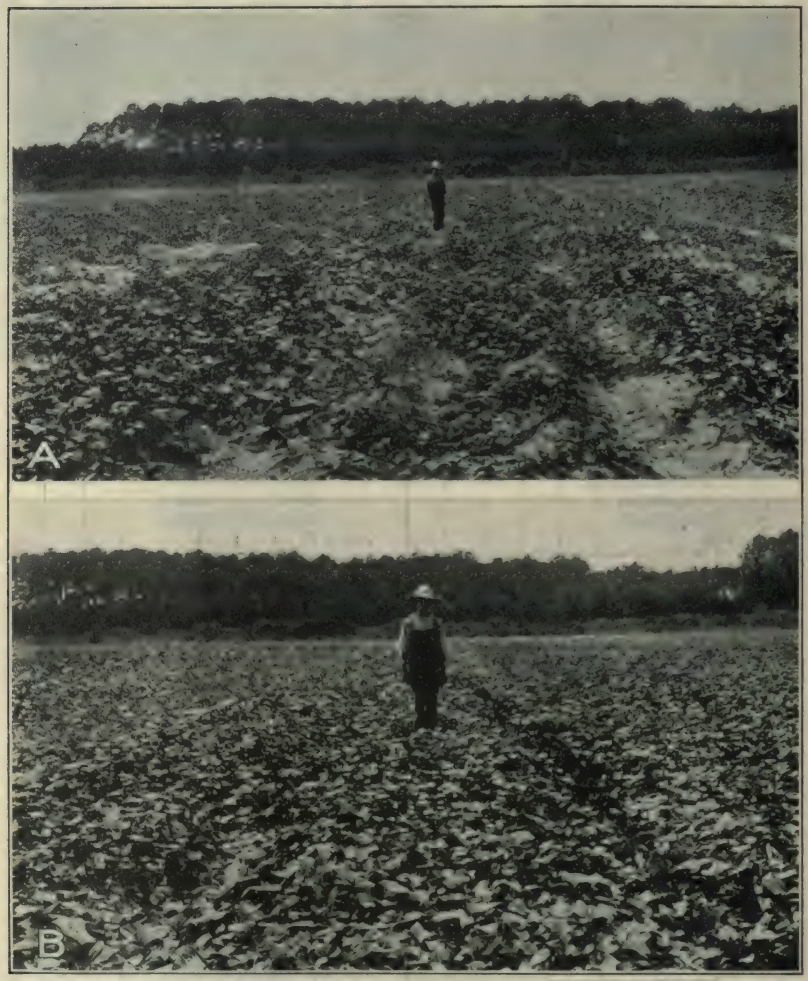


FIGURE 12.—Sweetpotatoes on Norfolk loamy fine sand fertilized with a 4-8-8 fertilizer applied at the rate of 1,000 pounds per acre before the plants were set: A, Nitrogen in the fertilizer derived from inorganic sources; B, nitrogen in the fertilizer derived two-thirds from mineral sources and one-third from organic sources of vegetable and animal origin

nitrate mixtures and ammonium sulphate mixtures gave smaller yields than did organic nitrogen mixtures. However, a mixture containing two-thirds mineral nitrogen and one-third organic nitrogen produced as large or larger yields than did organic nitrogen. Where sodium nitrate and ammonium sulphate were used the stands of sweetpotatoes were slightly poorer, which undoubtedly influenced the yields.

Approximately 20 per cent of the plants died in the sodium nitrate plots and 12 per cent in the ammonium sulphate plots. These plots were reset, but the late plants produced few sweetpotatoes. A perfect stand resulted where cottonseed meal and fish scrap were used, and there was no plant injury from the fertilizer deriving its nitrogen from a mixture of sodium nitrate, ammonium sulphate, and cottonseed meal. Figure 12, A, shows the results on stands of sweetpotatoes of fertilizer deriving all its nitrogen from inorganic sources, and in Figure 12, B, the results from fertilizer deriving nitrogen, two-thirds from inorganic sources and one-third from organic sources of vegetable and animal origin, are shown. Subsequent experiments revealed that mineral nitrogen, when used under certain conditions, may cause injury to newly set sweetpotato sprouts. It was difficult to maintain a stand where fertilizers containing 4 per cent of ammonia, derived from sodium nitrate and applied at the rate of 1,000 to 1,600 pounds an acre, were used. Experiments which give additional data on probable injury by fertilizer salts to young sweetpotato sprouts are reported and discussed in another section of this bulletin.

The results of experiments in which synthetic nitrogen salts were used as the sole source of nitrogen in mixed fertilizers, are given in Table 7 and are compared with results from sodium nitrate and ammonium sulphate. When the averages are considered, the yields from urea are somewhat lower than those from mineral nitrogen or other synthetic nitrogen salts. Experimental work reported in the following pages shows that better results are obtained when the nitrogen in a 4 per cent ammonia fertilizer is derived in part from mineral sources and in part from organic materials such as dried blood, fish scrap, tankage, and cottonseed meal. Experiments are in progress to determine the best ratio of mineral to organic nitrogen in mixed fertilizers for sweetpotatoes.

TABLE 7.—*Results of sweetpotato experiments with synthetic nitrogen salts as sources of nitrogen in fertilizers,*[1] *with phosphoric acid and potash*

Soil type and location	Year	Yield of sweetpotatoes per acre, with—				
		Sodium nitrate	Ammonium sulphate	Urea	Ammonium phosphate	Leunasalpeter
		Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*
Cecil sandy loam, A. R. Anthony farm, Catawba County	1927	170	163	155	133	146
	1928	291	293	226	270	226
Norfolk loamy fine sand, R. L. Griggs farm, Currituck County	1927	86	99	106	102	121
	1928	67	69	58	68	71
Average		153.5	156	136	143	141

[1] Fertilizer analyzing 4 per cent ammonia, 8 per cent phosphoric acid, and 8 per cent potash, applied at the rate of 750 pounds an acre on Cecil sandy loam and 1,800 pounds on Norfolk sandy loam.

POTASH SOURCES

The effect of potash from several sources in mixtures with nitrogen and superphosphate was studied in experiments on four soil types. The fertilizers were applied at the rate of 750 pounds an acre on all soils used in the experiments, except Norfolk loamy fine sand, in Currituck County, on which the rate of application was 1,400 and 1,800 pounds an acre. The results are given in Table 8.

TABLE 8.—*Results of sweetpotato experiments with potash from various sources in complete fertilizers,*[1] *with phosphoric acid and nitrogen, on several soil types in North Carolina*

Soil type and location	Year	Yield of sweetpotatoes per acre, with—		
		Potassium sulphate	Potassium chloride	Kainit
		Bushels	*Bushels*	*Bushels*
Portsmouth fine sandy loam, H. E. Patten farm, Craven County	1922	150	156	110
	1923	64	70	48
Norfolk sandy loam, C. G. Gaskell farm, Carteret County	1924	190	185	105
Cecil sandy loam, G. E. Rockett farm, Catawba County	1925	71	69	43
	1926	126	129	83
Cecil sandy loam, A. R. Anthony farm, Catawba County	1927	181	177	160
	1928	268	272	176
Norfolk loamy fine sand, Clyde Mathias farm, Currituck County	1925	162	138	99
Norfolk loamy fine sand, R. L. Griggs farm, Currituck County	1926	132	92	35
	1927	133	136	78
Average		147.7	142.4	93.7

[1] Fertilizer analyzing 4 per cent ammonia, 8 per cent phosphoric acid, and 6 per cent potash applied at rate of 750 pounds an acre, except in Currituck County experiments, which received 1,400 pounds in 1925 and 1,800 pounds in 1926 and 1927.

The outstanding result in these experiments, in which one form of potash was used as the entire source of that constituent, was the poor showing made by kainit. The yields from kainit were lower in each experiment than those from potassium sulphate or potassium chloride; the last two produced about the same result. In five experiments potassium chloride led and in five potassium sulphate led. The average yield in all the experiments is slightly higher with potassium sulphate. The effect of the potash sources on the growth of sweetpotato vines is shown in Figure 13.

FIGURE 13.—Effect of several potash sources, in mixed fertilizers with nitrogen and superphosphate, on stand and growth of sweetpotato vines on Norfolk loamy fine sand: A, Potassium sulphate, yield 133 bushels per acre; B, potassium chloride, yield 136 bushels per acre; C, kainit, yield 78 bushels per acre

The reduced yields from kainit may be attributed to its injurious effect on young sweetpotato plants. Considerable plant injury was observed in the kainit plots, especially on Norfolk loamy fine sand, on which it was necessary to reset the plants. The large percentage of readily soluble salts in fertilizers containing 8 per cent potash, derived from kainit, is apparently the cause of the plant injury observed. Reports on subsequent work give results of fertilizer-placement experiments, and detailed data on the salt content of the soil near the roots of plants, where fertilizers of different composition were used.

Potassium chloride and potassium sulphate have about equal value for sweetpotatoes on the soils used in the experiments. Kainit seems unsuitable as the sole source of potash, where a 6 to 8 per cent potash fertilizer is used, unless precautions are taken in applying the fertilizer.

FERTILIZER PLACEMENT AND TIME OF APPLICATION

On Norfolk loamy fine sand, injury to sweetpotato plants attributed to fertilizers has resulted in poor stands and delayed maturing of the crop. Loss of plants in the early part of the season can be reduced by methods of placing fertilizers in relation to the position of newly set plants, and timing application of fertilizers in relation to time of setting the plants. Results of experiments, made from 1928 to 1931, on this soil type are interesting in connection with placement of fertilizers, time of applying fertilizer mixtures, and time of applying separate fertilizer ingredients, nitrogen and potash.

Results of experiments with a fertilizer mixture containing 4 per cent ammonia, 8 per cent phosphoric acid, and 8 per cent potash, used at the rate of 1,000 and 1,600 pounds an acre are given in Table 9.

TABLE 9.—*Effect of applying fertilizers* [1] *at different locations, in relation to plants and time of application, on sweetpotatoes on Norfolk loamy fine sand, Boswood farm, Currituck County, N. C., 1928*

Method and time of application	Plants living when—		Yield per acre when—	
	1,000 pounds of fertilizer per acre were applied	1,600 pounds of fertilizer per acre were applied	1,000 pounds of fertilizer per acre were applied	1,600 pounds of fertilizer per acre were applied
	Per cent	*Per cent*	*Bushels*	*Bushels*
Fertilizers applied in plant row, mixed in soil and bedded on, 10 days before plants were set	90	92	85	97
Fertilizers applied in plant row, not mixed in soil and bedded on, 10 days before plants were set	92	87	87	92
Fertilizers applied to side of plant row, 3 inches from plants, 2 weeks after plants were set	100	100	93	100
Fertilizers applied broadcast on top of plant row, 2 weeks after plants were set	100	100	101	106
	Per cent		*Bushels*	
No fertilizer	100		28	

[1] Fertilizer containing 4 per cent ammonia, 8 per cent phosphoric acid, and 8 per cent potash, made from sodium nitrate, cottonseed meal, superphosphate, and potassium sulphate.

There was some injury to the young sweetpotato plants from the fertilizer applied in the row under the plants, as indicated by the percentage of plants which failed to survive and grow. Fertilizers

applied to the side of the plants or broadcast on top of the row after the plants had become established caused no injury and all plants survived. The plots having the best stands produced the largest yields.

Results of experiments with potassium chloride and kainit in a mixture with superphosphate, sodium nitrate, and cottonseed meal are given in Table 10. Kainit proved more injurious to young plants than the potassium chloride, possibly because of the amount of readily soluble salts in the mixture supplied in kainit. The kainit contained 12.5 per cent and the potassium chloride 50 per cent potash. Four times as much kainit as muriate of potash was required to make the 8 per cent potash mixture.

TABLE 10.—*Effect on sweetpotato growth and yield of time of applying potash on Norfolk loamy fine sand, Boswood farm, Currituck County, N. C., 1928* [1]

Method and time of application	Plants living when—			
	1,000 pounds of fertilizer per acre were used (potassium chloride source of potash)	1,600 pounds of fertilizer per acre were used (potassium chloride source of potash)	1,000 pounds of fertilizer per acre were used (kainit source of potash)	1,600 pounds of fertilizer per acre were used (kainit source of potash)
	Per cent	*Per cent*	*Per cent*	*Per cent*
All potash applied with mixture when plants were set	95	92	82	70
All potash applied with mixture 2 weeks before plants were set	98	97	85	78
One-fourth of the potash applied with mixture 2 weeks before plants were set, one-half 3 weeks after plants were set, and one-fourth 6 weeks after plants were set	100	100	97	96
One-half of the potash applied with mixture 3 weeks after plants were set and one-half 6 weeks after plants were set	98	95	95	90
No fertilizer	*Per cent* 97			

Method and time of application	Yields per acre when—			
	1,000 pounds of fertilizer per acre were used (potassium chloride source of potash)	1,600 pounds of fertilizer per acre were used (potassium chloride source of potash)	1,000 pounds of fertilizer per acre were used (kainit source of potash)	1,600 pounds of fertilizer per acre were used (kainit source of potash)
	Bushels	*Bushels*	*Bushels*	*Bushels*
All potash applied with mixture when plants were set	88	78	69	62
All potash applied with mixture 2 weeks before plants were set	114	122	88	98
One-fourth of the potash applied with mixture 2 weeks before plants were set, one-half 3 weeks after plants were set, and one-fourth 6 weeks after plants were set	106	123	95	99
One-half of the potash applied with mixture 3 weeks after plants were set and one-half 6 weeks after plants were set	106	126	95	100
No fertilizer	*Bushels* 29			

[1] 4–8–8 fertilizer was used in experiment. Phosphoric acid and nitrogen applied before plants were set. Phosphoric acid in mixture derived from superphosphate; nitrogen one-half from sodium nitrate and one half from cottonseed meal

Where potash was applied with the fertilizer mixture immediately before the plants were set, a high percentage of plants died following the use of kainit, and there was some loss of plants when potassium chloride was used. The loss was greater in each case with the larger quantity of fertilizer employed. It was less when the fertilizers were applied two weeks before planting. Between the time the fertilizers were applied and the time the plants were set there was sufficient rainfall to thoroughly wet the soil and diffuse the fertilizer. There was but slight loss of plants where kainit mixtures were used and practically no loss where potassium chloride mixtures were used, where one-fourth the potash was applied before the plants were set and the remainder as a side application after the plants had become established. The yields are generally in harmony with the stands on the plots.

Results of experiments with fertilizers containing superphosphate, potassium sulphate, and sodium nitrate in which sodium nitrate was the sole source of nitrogen in one case and a mixture of sodium nitrate and cottonseed meal was the source of nitrogen in another are given in Table 11. In one case the fertilizer containing all the nitrogen was applied before setting the plants, and in the other the nitrogen was applied after the plants had become established. The experiment was planned to study the effect of the application of nitrogen on the growth of young sweetpotato plants and subsequently on yield.

TABLE 11.—*Effect on sweetpotato growth and yield of time of applying nitrogen, on Norfolk loamy fine sand, Boswood farm, Currituck County, N. C., 1928* [1]

Method and time of application	Plants living when—			
	1,000 pounds of fertilizer per acre, having one-half the nitrogen from sodium nitrate and one-half from cottonseed meal, were used	1,600 pounds of fertilizer per acre, having one-half the nitrogen from sodium nitrate and one-half from cottonseed meal, were used	1,000 pounds of fertilizer per acre, having sodium nitrate as the source of all the nitrogen, were used	1,600 pounds of fertilizer per acre, having sodium nitrate as the source of all the nitrogen, were used
	Per cent	*Per cent*	*Per cent*	*Per cent*
All nitrogen applied with mixture 2 weeks before plants were set	95	92	86	78
One-fourth nitrogen applied with mixture 2 weeks before plants were set, one-half 3 weeks after plants were set, and one-fourth 6 weeks after plants were set	95	99	92	90
One-half nitrogen applied with mixture 3 weeks after plants were set and one-half 6 weeks after plants were set	97	95	94	96
All nitrogen applied 3 weeks after plants were set	94	97	96	94
	Per cent			
No fertilizer	97			

[1] A 4–8–8 fertilizer was used in the experiment. Phosphoric acid and potash applied 2 weeks before plants were set. Phosphate in fertilizer derived from superphosphate; potash from sulphate of potash.

Method and time of application	Yield per acre when—			
	1,000 pounds of fertilizer per acre, having one-half the nitrogen from sodium nitrate and one-half from cottonseed meal, were used	1,600 pounds of fertilizer per acre, having one-half the nitrogen from sodium nitrate and one-half from cottonseed meal, were used	1,000 pounds of fertilizer per acre, having sodium nitrate as the source of all the nitrogen, were used	1,600 pounds of fertilizer per acre, having sodium nitrate as the source of all the nitrogen, were used
	Bushels	*Bushels*	*Bushels*	*Bushels*
All nitrogen applied with mixture 2 weeks before plants were set	73	82	64	53
One-fourth nitrogen applied with mixture 2 weeks before plants were set, one-half 3 weeks after plants were set, and one-fourth 6 weeks after plants were set	88	92	89	91
One-half nitrogen applied with mixture 3 weeks after plants were set and one-half 6 weeks after plants were set	77	93	95	83
All nitrogen applied 3 weeks after plants were set	73	90	83	91
	Bushels			
No fertilizer	29			

When applied before the plants were set, fertilizers containing 4 per cent ammonia, of which the nitrogen was derived from sodium nitrate, caused injury to the crop as evidenced by the comparatively small percentage of plants that survived. A larger percentage of the plants survived when only one-fourth or one-half the nitrogen was contained in the fertilizer mixture used in the preplanting application. There was only a small loss of young plants where the 4 per cent ammonia fertilizer, having the nitrogen derived equally from sodium nitrate and cottonseed meal was used. A loss of 8 per cent of the plants where 1,600 pounds of the 4–8–8 fertilizer was used in the preplanting application may be attributed in part to the fertilizer. The loss of plants was small, about the same percentage as in the no-fertilizer plot, where the smaller application of sodium nitrate or of a mixture of sodium nitrate and cottonseed meal was used. The yields from the two fertilizers did not differ widely when the nitrogen was applied after the plants had become established. The data indicate that equally good yields can be produced from fertilizer deriving its nitrogen entirely from sodium nitrate as from a mixture deriving its nitrogen from sodium nitrate and an organic material, if application can be so made as not to injure young plants. The effect of fertilizer on the stand of sweetpotatoes when fertilizers are applied before and after plants are set is shown in Fig. 14.

From the data in Tables 10 and 11, it is apparent that readily soluble salts in fertilizers, such as sodium nitrate and kainit, are harmful to young sweetpotato plants when the fertilizer is placed in the plant row on Norfolk loamy fine sand in Currituck County. In experiments in 1929, 1930, and 1931, the soil around the roots of the plants was examined for soluble salts several weeks after the fertilizer applications were made. Attempts have been made to correlate the quantity of soluble salts in the soil, where several fertilizers were used,

with the percentage of plants dying and with yields. These experiments were made on Norfolk loamy fine sand at Coinjock, N. C. The soil is of the same type as that used in the production of early sweet-

FIGURE 14.—Effect of applying fertilizers before and after sweetpotato p'ants are set on Norfolk loamy fine sand: 1,000 pounds per acre of a 4–8–8 fertilizer, composed of sodium nitrate, superphosphate, and potassium sulphate were used and applied in plant row before plants were set (A) and as a side dressing two weeks after plants were set (B)

potatoes in Currituck County. The experiments were repeated on the same plots each year. Three years' data are given in Table 12.

TABLE 12.—*Effect of time of application and placement of fertilizers of different compositions on accumulation of water-soluble salts in soil around roots of sweetpotato plants, on survival of plants, and on yield of sweetpotatoes. Norfolk loamy fine sand, Boswood farm, Coinjock, N. C., 1929, 1930, and 1931*

Composition of fertilizers	Rate of application per acre	Data recorded	Placement and time of fertilizer application								
			In furrows, mixed in soil and ridged before plants were set			In furrows, not mixed in soil and ridged before plants were set			In furrows, one-half mixed in soil and ridged before plants were set, one-half 3 weeks after plants were set		
			1929	1930	1931	1929	1930	1931	1929	1930	1931
	Pounds										
(A) 4–8–8, P_2O_5 from superphosphate, K_2O from potassium chloride, N one-half from nitrate soda, one-half from cottonseed meal.	1,000	Soluble salts in soil [1] parts per million	165.0	275.0	200	215.0	390.0	500	160.0	290.0	200
		Plants living [2] per cent	95.0	82.0	98	92.9	84.0	94	93.4	93.0	99
		Yield per acre bushels	129.0	115.0	135	126.0	118.0	110	139.0	124.0	127
Do	1,600	Soluble salts in soil parts per million	165.0	300.0	300	290.0	410.0	600	235.0	300.0	200
		Plants living per cent	92.2	82.0	97	86.4	84.0	94	95.7	94.0	99
		Yield per acre bushels	154.0	119.0	148	167.0	95.0	130	165.0	125.0	136
(B) 4–8–8, P_2O_5 from superphosphate, K_2O from potassium chloride, N from nitrate soda.	1,000	Soluble salts in soil parts per million	245.0	340.0	200	360.0	385.0	700	185.0	335.0	200
		Plants living per cent	90.7	70.0	97	87.2	59.0	96	87.2	90.0	98
		Yield per acre bushels	62.0	96.0	136	108.0	80.0	88	104.0	112.0	133
Do	1,600	Soluble salts in soil parts per million	430.0	490.0	500	520.0	740.0	900	200.0	515.0	300
		Plants living per cent	80.0	48.0	95	80.0	79.0	90	90.6	89.0	97
		Yield per acre bushels	97.0	62.0	115	122.0	60.0	75	140.0	112.0	127
(C) 4–8–8, P_2O_5 from superphosphate, K_2O from kainit, N one-half from nitrate soda and one-half from cottonseed meal.	1,000	Soluble salts in soil parts per million	1,185.0	480.0	250	1,210.0	500.0	900	1,280.0	390.0	200
		Plants living per cent	82.2	45.0	98	73.9	21.0	81	85.0	76.0	98
		Yield per acre bushels	121.0	60.0	133	104.0	57.0	70	91.0	112.0	133
Do	1,600	Soluble salts in soil parts per million	1,445.0	915.0	300	1,535.0	950.0	1,500	330.0	415.0	200
		Plants living per cent	66.5	21.0	96	80.0	11.0	51	69.8	76.0	96
		Yield per acre bushels	154.0	44.0	142	163.0	41.0	62	133.0	104.0	192
(D) 16–32–32, P_2O_5 from ammonium phosphate, K_2O from potassium chloride, N from ammonium phosphate and urea.	250	Soluble salts in soil parts per million	145.0	430.0	200	195.0	230.0	500	120.0	210.0	200
		Plants living per cent	93.7	90.0	96	94.3	78.0	92	94.3	70.0	98
		Yield per acre bushels	97.0	151.0	106	101.0	143.0	121	130.0	149.0	104
Do	400	Soluble salts in soil parts per million	175.0	600.0	250	210.0	245.0	650	180.0	470.0	200
		Plants living per cent	90.0	78.0	94	97.9	64.0	74	92.0	82.0	97
		Yield per acre bushels	136.0	136.0	140	139.0	130.0	111	144.0	171.0	154
Average (4 fertilizers)		Yield per acre bushels	119.0	97.9	132	129.0	90.5	96	131.0	126.2	138

Composition of fertilizers	Rate of application per acre	Data recorded	Placement and time of fertilizer application: Side dressing, 3 weeks after plants were set			One-half as side dressing 3 weeks after plants were set, one-half 6 weeks after plants were set			Broadcast on top of rows, 3 weeks after plants were set			Average		
			1929	1930	1931	1929	1930	1931	1929	1930	1931	1929	1930	1931
	Pounds													
(A) 4–8–8, P_2O_5 from superphosphate, K_2O from potassium chloride, N one-half from nitrate soda, one-half from cottonseed meal.	1,000	Soluble salts in soil [1] parts per million	30	55.0	60	45	45.0	45	45	50	50			
		Plants living [2] per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	126	108.0	115	152	109.0	111	146	96	120	136	112	120
Do	1,600	Soluble salts in soil parts per million	45	50.0	60	40	50.0	50	50	55	50			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	136	101.0	163	170	108.0	140	167	115	139	160	111	143
(B) 4–8–8, P_2O_5 from superphosphate, K_2O from potassium chloride, N from nitrate soda.	1,000	Soluble salts in soil parts per million	25	45.0	45	50	50.0	50	70	40	45			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	129	116.0	85	136	114.0	85	115	157	101	109	113	105
Do	1,600	Soluble salts in soil parts per million	35	55.0	50	60	45.0	50	45	60	60			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	110	130.0	121	166	116.0	116	131	168	142	128	108	116
(C) 4–8–8, P_2O_5 from superphosphate, K_2O from kainit, N one-half from nitrate soda and one-half from cottonseed meal.	1,000	Soluble salts in soil parts per million	60	60.0	50	70	45.0	60	60	40	50			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	97	131.0	127	139	120.0	149	113	110	153	111	98	128
Do	1,600	Soluble salts in soil parts per million	75	50.0	60	60	60.0	60	60	50	50			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	139	118.0	185	179	122.0	134	114	130	181	147	93	149
(D) 16–32–32, P_2O_5 from ammonium phosphate, K_2O from potassium chloride, N from ammonium phosphate and urea.	250	Soluble salts in soil parts per million	60	50.0	50	50	60.0	45	70	45	60			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	124	139.0	109	128	131.0	72	130	124	78	118	140	98
Do	400	Soluble salts in soil parts per million	65	50.0	50	55	55.0	50	55	50	50			
		Plants living per cent	100	100.0	100	100	100.0	100	100	100	100			
		Yield per acre bushels	127	152.0	145	148	146.0	130	151	148	133	141	147	136
Average (4 fertilizers)		Yield per acre bushels	124	124.4	131	152	120.8	117	133	131	131			

	Results from no fertilizer: Section A			Section B			Section C			Section D		
Soluble salts in soil parts per million	50	50	50	60	50	50	55	50	60	60	50	50
Plants living per cent	100	100	100	100	100	100	100	100	100	100	100	100
Yield per acre bushels	33	56	27	38	62	22	34	60	22	29	47	20

[1] Water-soluble salts in soil around the roots of the plants determined on samples collected 3 weeks after plants were set and before the delayed applications of fertilizers were made.
[2] Percentage of plants living was determined by making counts of living plants in each plot 3 weeks after plants were set and before delayed applications of fertilizers were made.

Comparison is made of a fertilizer containing 4 per cent ammonia, 8 per cent phosphoric acid, and 8 per cent potash, having its nitrogen derived entirely from sodium nitrate, and of one having the nitrogen derived equally from sodium nitrate and cottonseed meal. Kainit and potassium chloride as sources of potash are also compared. A mixture made from synthetic concentrated materials was also used. The fertilizers were used at the rate of 1,000 and 1,600 pounds an acre, with different methods of application.

There was less accumulation of water-soluble salts in the soil around the roots of the plants three weeks after the fertilizers were applied where a 4–8–8 fertilizer having its nitrogen derived equally from sodium nitrate and cottonseed meal was used, than where a fertilizer of the same analysis but having all its nitrogen from sodium nitrate was used. There was a greater soluble-salt content in the soil near the plant roots where an 8 per cent potash mixture containing kainit was used than where one containing potassium chloride was used. The results with a concentrated fertilizer mixture are not definite. In the first year's experiments the soluble salts in the soil were less than where the commercial mixture A was used, in the second year the accumulation of the salts in the surface soil was greater from the concentrated fertilizer, and in the third year the salt content of the plots receiving the two fertilizers was about the same.

In most cases the amount of salts accumulated in the soil around the roots of the plants correlates in a general way with the survival of the young plants. There was only a moderate accumulation of salts in the soil near the plant roots where mixture A, deriving its nitrogen partly from sodium nitrate and partly from cottonseed meal, was used. However, the quantity concentrating in the soil was sufficient to cause death to a small percentage of the plants in this sandy soil when 1,000 and 1,600 pounds of fertilizer an acre were applied in the furrow before the plants were set. Where only half the nitrogen was applied with the mixture before the plants were set, the accumulation of salts was generally less, but sufficient to be fatal to a small percentage of the plants. There was a greater accumulation of salts within the root zone of the young plants where fertilizer B was used, and many plants died. This occurred whether the fertilizer was not mixed or was well mixed in the soil. Applying only half the nitrogen with the mixture before planting did not entirely alleviate the harmfulness of the mixture.

Mixture C, which contained 8 per cent of potash derived from kainit, was more severe on the young sweetpotato plants than was mixture A, which contained potassium chloride. The amount of soluble salts within the root zone of the plants was much greater (in mixture C than in mixture A) in the 1929 experiments and somewhat greater in the 1930 and 1931 experiments. The percentage of plants surviving was generally in harmony with the percentage of salts in the soil within the root zone of the plants. Plants which survived where mixture C was used produced well, and the yields generally compare favorably with those made with mixtures containing other potash salts.

The survival of plants where the concentrated mixture D was used was as great as with mixture A in the 1929 experiment. However, in

1930 the results were not so clear. Where the fertilizer was left unmixed with the soil, there was a greater accumulation of salts in the plant-root zone, accompanied by a greater fatality of plants in 1930. The salt accumulation the first year was not sufficient to injure the young plants severely. In the third year, there was considerable injury where the fertilizer was not mixed in the soil and a slight injury where it was well mixed in the soil.

It should be noted that where each of the four fertilizers was applied as a side dressing or broadcast on top of the plant row after the plants had become established in the soil, all plants survived and a perfect stand was maintained.

In all three years of the experiments there were more water-soluble salts in the soil within the root zone of the newly set plants (with the exception of two instances) where the fertilizers were left unmixed in the plant row before ridging than where the fertilizers were well mixed before ridging. Generally there was a greater loss of plants with a greater concentration of salts in the surface soil. The thorough mixing of the fertilizers in the soil is important in sweetpotato growing on sandy soils, especially when using fertilizers containing large percentages of readily soluble salts.

A comparison of yield of sweetpotatoes from the four fertilizers used on Norfolk loamy fine sand, is interesting. When the fertilizers were applied before planting, as is the general custom on this soil type in North Carolina, mixture A gave larger yields than mixture B or C. The fertilizer having both mineral and organic nitrogen proved better than that containing only mineral nitrogen, and the fertilizer containing potassium chloride proved better than the mixture containing kainit. The general relation between these fertilizers also held when half the fertilizer was used at the preplanting application and the remainder later as a side application. When the fertilizers were applied as a side dressing or broadcast on top of the ridge after the plants had become established, this relation did not hold and there was not a wide variation in yields from the different mixtures.

In 1929 and 1931 the yields from the use of concentrated mixture C were generally smaller than the yields from the use of mixture A. However, in 1930 use of the concentrated mixture generally resulted in higher yields.

When the yield data are considered with respect to placement of the fertilizers and time of application, it is apparent that the delayed applications have generally given best results. However, these differed with the composition of the fertilizer and the quantity applied. The yields from the mixture containing kainit and from that containing sodium nitrate as the sole source of nitrogen were in most cases decidedly better where the fertilizers were applied after the plants had become well rooted. The results do not show conclusively whether best results can be expected from applying the fertilizer broadcast on top of the plant row or from applying it as a side dressing after the plants have become established.

Results are given in Table 13 of 12 experiments in which a 4–8–8 mixture was applied under the plant row two weeks before the plants were set, as compared with those obtained by broadcast application

on top of the ridge two weeks after the plants were set. These results are generally in favor of broadcasting on top of the row after the plants have become established. The average yield in the 12 experiments where the fertilizers were applied under the row before planting was 109 bushels an acre, as compared with 118 bushels where the fertilizer was applied broadcast on the row after the plants had become rooted.

TABLE 13.—*Effect on growth and yield of sweetpotatoes of broadcasting a 4–8–8* [1] *fertilizer mixture on top of row after plants were set, as compared to applying the same mixture under plants before plants were set*

Year	Fertilizer application per acre	Yield per acre with—		Year	Fertilizer application per acre	Yield per acre with—	
		Fertilizer under plant row, 2 weeks before plants were set	Fertilizer broadcast on top of row, 2 weeks after plants were set			Fertilizer under plant row, 2 weeks before plants were set	Fertilizer broadcast on top of row, 2 weeks after plants were set
	Pounds	*Bushels*	*Bushels*		*Pounds*	*Bushels*	*Bushels*
1928	1,000	85	101	1930	1,200	74	97
1928	1,600	97	107	1930	1,200	97	117
1929	1,000	129	146	1931	1,000	94	100
1929	1,600	154	167	1931	1,600	110	139
1930	1,000	115	96	1931	1,200	120	146
1930	1,600	119	115				

[1] Percentages, respectively, of ammonia, phosphoric acid, and potash.

CONCENTRATED FERTILIZERS

In a preceding section of this bulletin, are reported experiments comparing the effects of several synthetic nitrogen and mineral salts. In these experiments the salts were used in a complete fertilizer containing 20 per cent of plant food and 80 per cent of a filler, either natural or added. In order to study the effects of concentrated fertilizer on sweetpotatoes, field experiments were made on Norfolk loamy fine sand in Currituck County, and the results are here reported.

The materials used in preparing the concentrated fertilizer mixtures were ammonium phosphate, monopotassium phosphate, potassium nitrate, potassium sulphate, ammonium nitrate, ammonium chloride, urea, ammonium sulphate, and sodium nitrate. The ammonium phosphate was a commercial product, containing 14 per cent ammonia and 60 per cent phosphoric acid. The monopotassium phosphate was made in the fertilizer and fixed nitrogen laboratory of the Bureau of Chemistry and Soils at the Arlington Experiment Farm, Rosslyn, Va., from volatilized phosphoric acid and commercial potassium hydroxide. It analyzed 52 per cent phosphoric acid and 44 per cent potash. The potassium nitrate and potassium sulphate were commercial products purchased on the market, the former containing 16 per cent ammonia and 44 per cent potash, and the latter containing 50 per cent potash. The ammonium nitrate had a nitro-

gen content of 42 per cent ammonia, the urea 56 per cent, and the ammonium chloride 31.5 per cent.

Potassium ammonium phosphate, a mixture of monoammonium and monopotassium phosphates, made in the fertilizer and fixed nitrogen laboratory, was also used. The steps in preparing this mixture are the treatment of potassium chloride with two equivalents of phosphoric acid at a temperature high enough to expel hydrochloric acid and form a solution of monopotassium phosphate in phosphoric acid. The excess phosphoric acid is then neutralized with ammonia. Potassium ammonium phosphate is a complete fertilizer in itself and possesses excellent physical and mechanical properties making it suitable for fertilizer use. It contains 6.5 per cent ammonia, 56 per cent phosphoric acid, and 17 per cent potash.

In 1926 cottonseed meal was used, to the extent of 10 per cent of the total weight of the fertilizer mixture, as a partial source of nitrogen, to insure satisfactory drillability. Many of the mixtures made in 1925 had caked and proved difficult to handle and distribute in the field. In 1927 the cottonseed meal employed as a conditioner was, however, reduced to 5 per cent of the total weight of the mixtures, as it had been found that this quantity was sufficient to keep them in good drillable condition.

In the investigation with concentrated fertilizers, two mixtures were used in the first year's experiments. A commercial fertilizer containing 6 per cent ammonia, 9 per cent phosphoric acid, and 6 per cent potash was used at the rate of 1,400 pounds an acre, and equivalent quantities of the concentrated fertilizer were used. The so-called commercial fertilizer was composed of materials used in commercial-fertilizer mixtures for many years, and its composition differed slightly in the different experiments reported. In the discussion this mixture is referred to as the older fertilizer, or ordinary commercial fertilizer.

The fertilizers were prepared early in February and stored until April. The two concentrated mixtures absorbed moisture and became gummy. The physical condition of both mixtures was such that they could not be applied with a fertilizer distributor. The concentrated mixtures which were diluted with sand were also slightly moist, and their distribution by means of a machine was difficult.

The fertilizers were distributed by hand in the seed furrow, mixed with the soil by running a plow in the row, then bedded on, and sweetpotato plants were set 10 days later.

A good stand of plants was obtained, although the season from the time of setting the sprouts until the sweetpotatoes were dug on August 30 was unusually dry. The vines grew normally and the differences in vegetative growth in the different plots were slight. The yields are given in Table 14.

TABLE 14.—*Effect of concentrated fertilizers*[1] *on yield of sweetpotatoes on Norfolk loamy fine sand*

Fertilizer mixture	Ingredients in fertilizer mixture	Ingredients applied per acre	Yield per acre
		Pounds	*Bushels*
A	Ammonium phosphate	183.4	
	Ammonium nitrate	162.6	
	Potassium phosphate	24.5	
	Potassium nitrate	51.5	
	Total	422.0	115.1
A-1	Same as A diluted with sand	1,400	117.0
B	Ammonium phosphate	210.0	
	Urea	97.0	
	Potassium sulphate	168.0	
	Total	475.0	100.8
B-1	Same as B diluted with sand	1,400	110.2
C	Superphosphate	787.5	
	Potassium sulphate	168.0	
	Sodium nitrate	147.0	
	Ammonium sulphate	112.0	
	Dried blood	175.0	
	Filler	10.5	
	Total	1,400.0	123.0
	No fertilizer		72.0

[1] Fertilizer used at the rate of 1,400 pounds per acre, 6–9–6 basis.

In 1926, 1927, and 1928 experiments were made on the same soil type and on the same farm as in 1925. Eighteen hundred pounds an acre on the basis of 6–9–6 fertilizer was used in 1926 and 1927, and 1,600 pounds of a 4–8–8 mixture in 1928 was used on ¼-acre plots. The experiments were extended to include six mixtures in 1926 and eight in 1927 and 1928. The composition of each fertilizer is given in connection with the yield data in Table 15.

TABLE 15.—*Effect of concentrated and commercial fertilizers on sweetpotatoes on Norfolk loamy fine sand*

Fertilizer mixture	Ingredients in fertilizer mixture	Ingredients in fertilizer to make—		Yield per acre		
		1,800 pounds of 6–9–6 used in 1926 and 1927	1,600 pounds of 4–8–8 used in 1928	1926	1927	1928
		Pounds	*Pounds*	*Bushels*	*Bushels*	*Bushels*
A	Ammonium phosphate	265.0	267.0			
	Ammonium nitrate	68.0	64.7			
	Potassium ammonium phosphate	63.0				
	Potassium nitrate	221.0				
	Potassium sulphate		249.5			
	Cottonseed meal	[1] 68.0	31.2			
	Total	685.0	612.4	190	132	163
B	Ammonium phosphate	338.0	67.0			
	Urea	105.0	48.0			
	Potassium sulphate	216.0	249.5			
	Cottonseed meal	[1] 72.0	30.5			
	Total	731.0	395.0	200	138	176

TABLE 15.—*Effect of concentrated and commerical fertilizers on sweet potatoes on Norfolk loamy fine sand*—Continued

Fertilizer mixture	Ingredients in fertilizer mixture	Ingredients in fertilizer to make—		Yield per acre		
		1,800 pounds of 6–9–6 used in 1926 and 1927	1,600 pounds of 4–8–8 used in 1928	1926	1927	1928
		Pounds	*Pounds*	*Bushels*	*Bushels*	*Bushels*
C	Superphosphate	1,013.0	800.0			
	Potassium sulphate	216.0	249.5			
	Sodium nitrate	189.0	89.0			
	Ammonium sulphate	144.0	64.0			
	Dried blood	225.0	155.0			
	Filler	13.0	243.0			
	Total	1,800.0	1,600.5	179	158	184
D	Ammonium phosphate	338.0	267.0			
	Ammonium chloride	183.0	85.5			
	Potassium sulphate	216.0	249.5			
	Cottonseed meal	81.0	32.0			
	Total	818.0	634.0	120	113	162
E	Ammonium phosphate	338.0	267.0			
	Ammonium sulphate	236.0	106.0			
	Potassium sulphate	216.0	249.5			
	Cottonseed meal	[1] 86.0	33.5			
	Total	876.0	656.0	118	131	179
F	Triple phosphate	360.0	276.0			
	Urea	181.0	109.5			
	Potassium sulphate	216.0	249.5			
	Cottonseed meal	[1] 83.0	33.5			
	Total	840.0	668.5	140	136	119
G	Potassium ammonium phosphate.	290.0	229.0			
	Urea	117.5	26.0			
	Potassium nitrate	134.0	202.0			
	Cottonseed meal	28.5	24.0			
	Total	570.0	481.0		150	137
H	Potassium ammonium phosphate.	290.0	229.0			
	Ammonium sulphate	260.0	58.5			
	Potassium nitrate	134.0	200.5			
	Cottonseed meal	36.0	25.5			
	Total	720.0	513.5		136	139
I	Ammonium phosphate	338.0	267.0			
	Sodium nitrate	317.0	145.0			
	Potassium sulphate	228.0	249.5			
	Cottonseed meal	47.0	35.5			
	Total	930.0	697.0		180	138
	No fertilizer			53	31	35

[1] Half this amount of cottonseed meal was used in 1927.

In 1926 cottonseed meal was added in quantities amounting to 10 per cent of the weight of the mixture in each concentrated fertilizer, and in 1927 and 1928 cottonseed meal amounting to 5 per cent of the weight of the mixture was added to keep it in a desirable physical condition. The fertilizers were mixed early in February of each year and stored until applied in April. A desirable physical condition of the mixtures was maintained in most of the fertilizers. The treble phosphate mixture with urea (F) became gummy and the mixture of

urea and ammonium phosphate (B) was slightly moist but its condition was not undesirable. The other fertilizer did not absorb moisture or become caked. All the fertilizers except the treble phosphate-urea mixture were applied without difficulty by a fertilizer distributor. The application was made 14 days before the plants were set, and the fertilizer was well mixed in the soil.

In 1926 the season was again very dry, but no severe injury to the sweetpotatoes was noted. Growth was very slow in the early part of the summer, and the vines where fertilizer D, containing ammonium chloride, was used did not make a good growth, nor did they have a desirable green color at any time during the summer.

In 1927 and 1928 the plants again grew well and appeared thrifty in most of the plots. Early in the summer of 1927 it was noted that the plants on plot D, where the fertilizer contained ammonium chloride, had a pale-yellow color and were growing only slightly better than those on the no-fertilizer plots. A few plants died. Notes made on July 25 show the relative stand and condition of the crop. The data are given in Table 16.

TABLE 16.—*Condition of sweetpotato vines on July 25, 1927 and 1928, grown with concentrated and commercial fertilizers*

Fertilizer mixture	Color of vines	Area covered by vines	1927		1928	
			Relative condition considering stand and appearance	Stand	Relative condition considering stand and appearance	Stand
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
A	Dark green	92	90	90	95	100
B	do	90	98	95	92	100
C	do	98	100	95	100	100
D	Pale green	85	85	80	92	100
E	Dark green	96	97	95	96	100
F	do	92	95	90	94	100
G	do	98	100	98	95	100
H	do	93	92	98	95	100
I	do	90	90	92	95	100
No fertilizer	Pale green	85	40	98	25	100

In 1926 the largest yields were obtained from the use of concentrated fertilizers A and B, which produced 11 and 21 bushels more, respectively, than fertilizer C. The yields from the use of fertilizers D, E, and F were smaller.

In 1927 the commercial mixture C gave larger yields than seven of the concentrated mixtures. Concentrated mixture I gave the largest yield, but this relation did not hold the following year. In 1928 the largest yielding plot was that fertilized with the commercial mixture C.

In 1926 and 1928 concentrated mixture F, which contained triple phosphate and urea, gave a smaller yield by 60 and 57 bushels, respectively, than did mixture B which had its phosphate derived from ammonium phosphate and its nitrogen partly from ammonium phosphate and partly from urea. In 1927 the yields from the two fertilizers were very close but slightly in favor of mixture B.

Fertilizer D, containing ammonium phosphate, ammonium chloride, and potassium sulphate, gave a comparatively low yield each

year. This was more marked in 1926 and 1927. The disturbing factor in this mixture is undoubtedly ammonium chloride. In 1928 a lower nitrogen fertilizer was used and the amount of ammonium chloride was probably not sufficient to exert a retarding effect. It was noted that there was no detrimental effect that year on the young plants when first set, but there was some retardation of vine growth. This was overcome in the late season, and the yields of sweetpotatoes fertilized by mixture D compared favorably with yields from some of the other concentrated mixtures but were not so good as yields from the commercial fertilizer.

In 1927 an experiment on a somewhat larger scale was made in addition to those reported in Table 15. The test was carried out on two ½-acre plots, one of which was treated with a fertilizer made from older commercial materials and the other with a mixture of concentrated materials. The fertilizer used in each case analyzed 4–8–8 and was applied at the rate of 1,800 pounds an acre. The fertilizer was supplied to the cooperating farmer and applied by him with the fertilizer distributor used in applying fertilizers to his commercial crop.

A good stand was obtained in each ½-acre plot, and a healthy growth of vines was produced. The vines retained a desirable dark-green color throughout the growing season. Ninety-eight per cent of the plants lived on the half acre fertilized with the commercial mixture and 95 per cent on the half acre treated with the concentrated fertilizer.

The sweetpotato yields and the composition of the two fertilizers are given in Table 17. The commercial mixture produced a larger yield by 16.5 bushels than did the concentrated.

TABLE 17.—*Yields from two ½-acre plots of sweetpotatoes fertilized* [1] *with a commercial and a concentrated mixture, on Norfolk loamy fine sand, Currituck County, N. C., 1927*

Kind of fertilizer	Composition of fertilizer	Quantity applied per acre	Yield of sweetpotatoes per acre
		Pounds	*Bushels*
Concentrated	Ammonium phosphate	300	
	Urea	58	
	Potassium sulphate	306	
	Cottonseed meal	70	
	Total	734	148.5
Commercial	Superphosphate	900	
	Sodium nitrate	100	
	Ammonium sulphate	72	
	Fish scrap	152	
	Cottonseed meal	224	
	Potassium sulphate	306	
	Filler	46	
	Total	1,800	165.0

[1] Fertilizer applied at a rate to equal 1,800 pounds per acre of a 4–8–8 analysis.

The addition of sodium nitrate and ammonium sulphate or of cottonseed meal and tankage to some of the concentrated mixtures used in the preceding experiments did not appreciably improve them for sweetpotato production. In the experiments reported in Table 18,

one-fourth of the nitrogen from the synthetic salts in three mixtures, namely, A, B, and F, was replaced by mineral nitrogen in one case and by organic nitrogen of vegetable and animal-waste origin in another. There was no consistent increase in sweetpotato yield from mixtures containing the substitutes over the yield from the mixture deriving its nitrogen entirely from the more concentrated synthetic salts. This was generally the case whether the fertilizer was all applied before the plants were set or whether only half the quantity was applied before planting and half as a side dressing 30 days after planting. The yields from the concentrated mixtures were not so great as from mixture C which was composed entirely of the commercial fertilizer materials.

TABLE 18.—*Effect on sweetpotatoes of concentrated fertilizer containing small quantities of mineral and organic nitrogen, on Norfolk loamy fine sand, Currituck County, N. C.*

Plot No.	Composition of fertilizer	Fertilizer per acre [1]	Yield per acre with—								Average yield
			Fertilizer applied before planting				Fertilizer applied one-half before planting and one-half 30 days after plants were set				
			1929	1930	1931	Average	1929	1930	1931	Average	
		Pounds	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
A–1	Ammonium phosphate, ammonium nitrate, and potassium sulphate	626	96	152	119	122.3	129	150	123	134.0	128.1
A–2	Same as A–1, except one-fourth of nitrogen was from sodium nitrate and ammonium sulphate	667	110	151	113	124.7	124	129	125	126.0	125.3
A–3	Same as A–1, except one-fourth of nitrogen was from cottonseed meal and tankage	751	107	184	128	139.7	126	132	132	130.0	134.8
B–1	Ammonium phosphate, urea, and potassium sulphate	604	88	165	121	124.7	116	137	132	128.3	126.5
B–2	Same as B–1, except one-fourth of nitrogen was from sodium nitrate and ammonium sulphate	657	93	161	108	120.7	109	162	109	126.6	123.6
B–3	Same as B–1, except one-fourth of nitrogen was from cottonseed meal and tankage	741	98	147	123	122.7	107	138	137	127.3	125.0
F–1	Treble superphosphate, urea, and potassium sulphate	713	92	149	119	120.0	112	157	115	128.0	124.0
F–2	Same as F–1, except one-fourth of nitrogen was from sodium nitrate and ammonium sulphate	732	117	----	----	----	100	----	----	----	----
F–3	Same as F–1, except one-fourth of nitrogen was from cottonseed meal and tankage	875	117	----	----	----	112	----	----	----	----
C	Superphosphate, potassium sulphate, sodium nitrate, ammonium sulphate, cottonseed meal, and tankage	1,600	129	157	135	140.3	132	167	138	145.7	143.0
	No fertilizer	0	37	62	27	42.0	----	----	----	----	----

[1] Equivalent to 1,600 pounds per acre of 4–8–8 fertilizer.

Experiments with concentrated fertilizers containing dolomitic limestone and minor essential plant foods, such as manganese, copper, zinc, nickel, and boron did not give consistent results, as shown in Table 19. Their use resulted in some increases over the use of concentrated mixtures, but in no case was the yield so large as in plot C, containing the commercial materials. The soil of the plots where no limestone was used was acid, having a pH of 5.8 to 6.0. The minor chemicals were mixed in the fertilizer and applied with the mixture. Manganese sulphate alone, with the concentrated fertilizer, and in concentrated fertilizers with zinc sulphate, copper sulphate, nickel sulphate, and boron, gave some minor increases over its check when divided fertilizer application was made but practically no increase when the fertilizer was all applied before planting.

TABLE 19.—*Effect of concentrated fertilizers, containing minor essential chemicals, on sweetpotatoes on Norfolk loamy fine sand, Currituck County, N. C.*

Plot No.	Fertilizer treatment	Fertilizer per acre [1]	Yield per acre with—						Average yield
			Fertilizers applied before planting			One-half fertilizer applied before planting and one-half 30 days after plants were set			
			1930	1931	Average	1930	1931	Average	
		Pounds	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
B–1	Ammonium phosphate, urea, and potassium sulphate	604	147	121	134.0	137	132	134.5	134.2
B–4	Same as B–1, plus manganese sulphate [2]	654	143	116	129.5	152	130	141.0	135.2
B–5	Same as B–1, plus manganese sulphate, copper sulphate, zinc sulphate, nickel sulphate, and boron [3]	672	151	120	135.5	145	137	141.0	138.2
B–6	Ammonium phosphate, urea, potassium sulphate, and limestone [4]	604	135	118	126.5	140	120	130.0	128.2
B–7	Same as B–6, plus manganese sulphate [2]	654	136	124	130.0	149	130	139.5	134.8
B–8	Same as B–6, plus manganese sulphate, zinc sulphate, nickel sulphate, and boron [3]	672	145	128	136.5	150	137	143.5	140.0
C	Superphosphate, potassium sulphate, sodium nitrate, ammonium sulphate, cottonseed meal, and tankage	1,600	157	135	146.0	167	138	152.5	149.2
	No fertilizer	0	63	27	45				

[1] Equivalent to 1,600 pounds per acre of 4–8–8 fertilizer.
[2] Manganese sulphate used at rate of 50 pounds per acre.
[3] Manganese sulphate used at rate to add 50 pounds per acre; zinc sulphate, copper sulphate, zinc sulphate, nickel sulphate, and boron, 3 pounds per acre.
[4] Dolomitic limestone was applied in the fertilizer furrow when fertilizers were applied at rate of 500 pounds per acre.

The dolomitic limestone was applied in the plant furrow two weeks before the plants were set. The soil during the growing season was neutral to slightly alkaline and maintained a pH of 7.0 to 7.4. The addition of limestone to the soil did not make it more productive of sweetpotatoes. There was generally an increase in yield from the manganese and the manganese, zinc, copper, and nickel on the limed soil, but the result is not marked, possibly because of the apparently depressing effect of the limestone.

DISCUSSION

The yields of sweetpotatoes from concentrated fertilizers were not generally so high as from ordinary fertilizers used as a means of comparison in this work. In the experiments reported in this bulletin, 2 concentrated mixtures were used in 1925, 5 in 1926, and 8 in 1927 and 1928. In the first year the 2 concentrated mixtures gave a lower yield than the commercial. In the second year, 2 of the concentrated mixtures gave a higher yield, in the third year 1 concentrated mixture gave a much higher yield, but 7 gave a lower yield than the commercial mixtures. In the fourth year all 8 concentrated mixtures fell behind the commercial.

Concentrated mixture A, consisting of ammonium phosphate, potassium-ammonium phosphate, ammonium nitrate, and potassium nitrate, and concentrated mixture B, consisting of ammonium phosphate, urea, and potassium sulphate, gave the largest yields of the concentrated mixtures in 1926 and in 1928. In 1927 two other mixtures gave larger yields.

Concentrated mixture D, consisting of ammonium phosphate, ammonium chloride, and potassium sulphate, gave the poorest vine growth and the poorest yield of sweetpotatoes in 1926 and 1927. In 1928 the yield with this fertilizer was below that with the commercial fertilizer, but better than with some of the concentrated mixtures. In the 1928 experiments a lower nitrogen mixture was used and 85.5 pounds per acre of ammonium chloride were used as compared to 183 pounds in 1926 and 1927. Ammonium chloride seems to be the disturbing factor in this mixture; the smaller quantities used in 1927 apparently were not sufficient to retard growth.

Although the concentrated mixtures did not give as good yields as ordinary commercial fertilizer, most of the concentrated fertilizers used gave good results. The use of small quantities of mineral nitrogen or of organic nitrogen of vegetable and animal-waste origin, with concentrated mixtures containing principally synthetic nitrogen salts, did not appreciably improve them for the production of sweetpotatoes on Norfolk loamy fine sand, nor did the addition of limestone or of minor essential chemicals, such as manganese, copper, zinc, nickel, and boron, cause the fertilizer to produce appreciably larger yields of sweetpotatoes on this soil.

SUMMARY

The results of fertilizer experiments with sweetpotatoes made in North Carolina on Norfolk sandy loam, Portsmouth fine sandy loam, Cecil sandy loam, and Norfolk loamy fine sand are given. A study was made (1) of fertilizers of different ratios of nitrogen, phosphoric acid, and potash for sweetpotatoes, (2) of various nitrogen sources, (3) of various potash sources, (4) of quantities of fertilizers, (5) of time of application and placement of fertilizers, in relation to the plant, and (6) of concentrated fertilizers.

The fertilizer requirement as to ratio of nitrogen, phosphoric acid, and potash differs slightly with the soil type. For Norfolk sandy loam in the central coastal plain, best results were obtained with fertilizers containing a small percentage of phosphoric acid, 3 to 4 per cent ammonia, and 9 to 10 per cent potash; for Portsmouth fine sandy loam of the central coastal plain, best results were obtained with mixtures containing 3 to 4 per cent ammonia, 3 to 4 per cent phos-

phoric acid, and 8 to 9 per cent potash; for Cecil sandy loam of the piedmont section, best results were obtained with mixtures containing 2 to 4 per cent ammonia, 4 to 6 per cent phosphoric acid, and 7 to 9 per cent potash; and for Norfolk loamy fine sand of the northern coastal plain, fertilizers giving best results contained about 3 per cent ammonia, 3 to 6 per cent phosphoric acid, and 6 to 9 per cent potash. The fertilizer requirements for sweetpotatoes, as regards ratio of nitrogen, phosphoric acid, and potash, of the soil types worked with, do not differ widely. Commercial fertilizers used for sweetpotatoes differ greatly in composition. In the larger sweetpotato sections, the fertilizers generally used contain from 3 to 4 per cent ammonia, 8 to 10 per cent potash, and about 8 per cent phosphoric acid. The data obtained in the experimental work, on soils which in previous years have received fertilizers containing high percentages of phosphoric acid, show largest yields with fertilizer mixtures containing a lower ratio than 8 per cent phosphoric acid, to 4 per cent ammonia and 8 per cent potash. For virgin soils or soils previously planted to crops without the additions of phosphate fertilizers, an 8 per cent phosphoric acid mixture would probably be required for best results.

For sweetpotatoes grown on Norfolk sandy loam, Portsmouth fine sandy loam, and Cecil sandy loam, fertilizers applied at the rate of 750 and 1,000 pounds an acre gave better yields than smaller or larger quantities. The increased yield from 1,000 pounds an acre over 750 pounds was usually small and of doubtful economic importance. For the Norfolk loamy fine sand larger quantities were profitable, from 1,200 to 1,500 pounds an acre giving best results.

On heavy soil types, synthetic and mineral nitrogen salts gave as large yields as mixtures of these with organic nitrogen materials. On Norfolk loamy fine sand, where fertilizers are used at a rate ranging from 1,000 to 1,500 pounds an acre, a 4 per cent nitrogen mixture, with nitrogen derived entirely from mineral sources, was injurious to newly set sweetpotato plants and resulted in poor stands and reduced yields. It may be concluded that fertilizer for sweetpotatoes on sandy soils should have its nitrogen derived partly from mineral or synthetic nitrogen and partly from organic materials.

Potassium sulphate and potassium chloride proved to be satisfactory sources of potash for sweetpotatoes. The yields produced by both were practically the same. Kainit as the sole source of potash in an 8 per cent potash mixture, when used at the rate of 1,400 pounds an acre, caused injury to newly set plants, resulting in poor stands and reduced yields. On all the soils worked with, kainit gave smaller yields than did potassium sulphate or potassium chloride.

Complete fertilizers containing kainit as the source of potash and fertilizers containing nitrate of soda as the source of nitrogen caused injury to sweetpotato plants when applied before the plants were set in the row and ridged, but no injury was observed when the fertilizers were applied either as a side dressing or broadcast on top of the plant row after the plants were well rooted. When the fertilizer was applied in the plant row before planting, the concentration of soluble salts in the soil within the root zone of the young plants was sufficient to kill the plants. This accumulation of soluble salts in the surface soil was not great where fertilizer containing potassium sulphate

or potassium chloride was used or when fertilizer having its nitrogen derived equally from mineral salts and from organic material was used. The percentage of dead plants was generally correlated with the amount of salts concentrated in the soil within the root zone of the young plants.

Fertilizers applied broadcast on top of the plant row or applied as a side dressing after the plants were well established caused no injury to young plants and produced larger yields than fertilizers applied in the row before the plants were set.

Concentrated fertilizers, made primarily from synthetic chemicals, gave good results with sweetpotatoes on Norfolk loamy fine sand when applied in the furrow before setting the plants, if precautions were taken to apply the fertilizer 10 days before setting the plants and mix it in the soil. The yields from concentrated fertilizers were not so large as from ordinary fertilizer mixtures made from the older materials. The addition of dolomitic limestone or of minor essential elements, such as manganese, zinc, copper, boron, and nickel, to concentrated fertilizers did not markedly improve them for sweetpotato production on Norfolk loamy fine sand.

LITERATURE CITED

(1) Bledsoe, R. P., and Skinner, J. J.
1929. fertilizer ratio experiments, conducted on cecil sandy clay loam. cotton, corn, and wheat grown in rotation. Ga. Agr. Expt. Sta. Bul. 151, 31 p., illus.

(2) Ferris, E. B., and Anderson, W. S.
1926. a report of work at south mississippi branch station for 1926. Miss. Agr. Expt. Sta. Bul. 238, 18 p.

(3) Geise, F. W.
1926. the influence of nitrogen, phosphorus, and potash, separately and in combination, on sweet potato production. Amer. Soc. Hort. Sci. Proc. (1925) 22:363–370, illus.

(4) ———
1929. fertilizer studies and the production of sweet potatoes. Md. Agr. Expt. Sta. Bul. 311, 38 p., illus.

(5) Hotchkiss, W. S.
1921. sweet potato fertilizer experiments at substation no. 2. Tex. Agr. Expt. Sta. Bul. 277, 7 p.

(6) Houghland, G. V. C.
1928. fertilizer studies with sweet potatoes. Soil Sci. 26:291–304.

(7) Johnson, T. C., and Zimmerley, H. H.
[1924]. effect of certain sodium and potassium salts on sweetpotato production in eastern virginia. Amer. Soc. Hort. Sci. Proc. (1923) 20:155–162.

(8) Keitt, T. C.
1912. sweet potato investigation. S. C. Agr. Expt. Sta. Bul. 165, 43 p., illus.

(9) Knapp, B.
1922. farm helps from experiments. Ark. Agr. Expt. Sta. Bul. 181, 103 p., illus.

(10) Noll, C. F., Schreiner, O., and Skinner, J. J.
1915. fertilizer ratio experiments with grass on hagerstown loam. Penn. Agr. Expt. Sta. Ann. Rpt. 1913/14 (pt. 2):22–36, illus.

(11) Pate, W. F., and Skinner, J. J.
1924. results of fertilizer experiments with cotton and irish potatoes on some of the principal soil types of north carolina. N. C. Dept. Agr. Bul. Sept., 1924, 69 p., illus.

(12) Quinn, J. T.
[1926]. some effects of fertilizers on sweet potatoes. Amer. Soc. Hort. Sci. Proc. (1925) 22: 360–362.

(13) SCHERMERHORN, L. G.
[1924]. INFLUENCE OF FERTILIZERS ON THE YIELD AND FORM OF THE SWEET POTATO. Amer. Soc. Hort. Sci. Proc. (1923) 20 : 162–165.
(14) ———
1924. SWEET POTATO STUDIES IN NEW JERSEY. N. J. Agr. Expt. Sta. Bul. 398, 19 p., illus.
(15) SCHREINER, O., and SKINNER, J. J.
1918. THE TRIANGLE SYSTEM FOR FERTILIZER EXPERIMENTS. Jour. Amer. Soc. Agron. 10 : 225–246, illus.
(16) SCOTT, J. M.
1920. SWEET POTATO FERTILIZER EXPERIMENT. Fla. Agr. Expt. Sta. Bul. 156, p. [59]–63, illus.
(17) STUCKEY, H. P.
1914. SWEET POTATOES, CULTURE, STORING AND STUDIES IN FERTILIZING. Ga. Agr. Expt. Sta. Bul. 107, p. [83]–112, illus.
(18) UNITED STATES DEPARTMENT OF AGRICULTURE.
1931. AGRICULTURAL STATISTICS: FRUITS AND VEGETABLES. U. S. Dept. Agr. Yearbook 1931 : 780–781, illus.
(19) VOORHEES, E. B.
1891. EXPERIMENTS WITH FERTILIZERS UPON WHITE AND SWEET POTATOES. N. J. Agr. Expt. Sta. Spec. Bul. P, 24 p.
(20) ZIMMERLEY, H. H.
1929. SWEET POTATO FERTILIZERS. Va. Truck Expt. Sta. Bul. 66, p. [701]–717, illus.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Soil Investigations	A. G. MCCALL, *Chief.*
Division of Soil Fertility	OSWALD SCHREINER, *Principal Biochemist, in Charge.*

47

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 334 SEPTEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

THE EFFECT OF INORGANIC ACIDS ON THE PHYSICAL PROPERTIES OF WATERLEAF RAG BOND PAPER

By T. D. JARRELL, *Associate Chemist*, J. M. HANKINS, *Junior Chemist*, and F. P. VEITCH, *Principal Chemist in Charge, Industrial Farm Products Division, Chemical and Technological Research, Bureau of Chemistry and Soils*

CONTENTS

	Page		Page
Introduction	1	Discussion of results—Continued.	
Review of the literature	2	Effect of aluminum sulphate	11
Experimental procedure	3	Effect of sulphuric acid	12
Results	5	Effect of hydrochloric acid	13
Discussion of results	9	Conclusions and summary	14
Untreated control	10	Literature cited	15

INTRODUCTION

Acid in paper has long been considered a factor in causing its deterioration. Various investigators have stated that acid in the finished paper may be due to (1) the use of aluminum sulphate in the sizing process, (2) a chemical reaction taking place in the paper after manufacture, or (3) the absorption of acidic sulphur oxides from the atmosphere.

REVIEW OF THE LITERATURE

In 1882 Feichtinger (*7*)[1] reported that paper containing rosin sizing has an acid reaction due to sulphuric acid, which he regarded as injurious to the durability of paper. Wurster (*19*) and Herzberg (*10*), on the other hand, expressed the opinion that when sodium and calcium chlorides resulting from the use of bleaching powder are not thoroughly washed from the pulp and aluminum sulphate is subsequently added, aluminum chloride, a compound which readily gives off free hydrochloric acid, may be formed. Both these authors agreed that small quantities of hydrochloric acid attack cellulose. In 1898 the committee [Great Britain] on the deterioration of paper in discussing the causes of deterioration of rag paper (*6*) said:

> * * * the disintegration may be generally referred to acidity. The acids may have been present in the original paper as made; or may have resulted from reactions going on in the paper itself after making; or lastly may have been due to products of gas combustion.

[1] Italic numbers in parentheses refer to Literature Cited, p. 15.

129093°—32

Winkler (*18*) treated paper with dilute solutions (1:100 to 1:50,000) of hydrochloric and sulphuric acids and after 3½ years' observation concluded that very small quantities of mineral acids are injurious to paper and that sulphuric acid causes greater deterioration than does hydrochloric acid.

Edlund (*5*) determined the amount of sulphuric acid present as aluminum sulphate, mainly in papers sized with animal sizing, by extracting the paper with warm water and titrating the extract with 0.1 normal potassium hydroxide, using phenolphthalein as indicator. He examined eight samples by this method and found from 0.3 to 1.6 per cent sulphuric acid. Edlund raised the question whether the presence of such large quantities of an acid salt, such as aluminum sulphate, might injuriously affect the durability of paper. Lester (*14*) treated cotton cloth with hydrochloric or sulphuric acid of various strengths and then dried the cloth by ironing. He found that the degree of tenderness caused by the two acids is about the same and concluded that the maximum allowable in cotton cloth appears to be 0.01 per cent of free hydrochloric acid. Coward, Wood, and Barrett (*4*) did some work on the effect of various acids, including hydrochloric and sulphuric, on cotton fabrics. They found that tendering of cotton fabrics in dilute aqueous solutions of acids is roughly parallel to the pH of the solution at constant temperature and is a function of the temperature of the solution. Hall (*9*) reported an investigation conducted at the Government testing institute in Stockholm, Sweden, on the permanence of paper. He concluded that acidity of paper may be caused by rosin sizing and warned against the use of an unnecessary excess of aluminum sulphate in making the rosin size. Hall claimed that the acid number of rosin-sized papers as determined by the Swedish Government testing institute, a method now often used in this country, should not exceed about 20, which corresponds to about 0.08 per cent SO_3. Hoffman (*11*) determined the effect of acidity on the bursting strength of about 24 samples of commercial papers, including wrapping, envelope, and label. He concluded that the higher the acid number of the paper and the lower the pH value of the water extract, the greater in general was the decrease in bursting strength when the paper was artificially aged by heating for 24 hours at 85° C. He did not determine the effect on folding endurance. Hoffman (*11, p. 60*) stated:

> If the acid number of paper is below about 25, as measured by the Swedish Government testing institute's method, the paper does not decrease appreciably in bursting strength when heated at 85° C. for periods as long as 72 hours.

He also concluded from his data that when the pH of the water extract is greater than 4.5 there is no great loss in bursting strength when the paper is heated for 24 hours at 85°. Hoffman, in another article (*12*), expressed the opinion that the acidity caused by the aluminum sulphate used to set the rosin size is an important factor in the deterioration of paper.

On the other hand, Baker (*1*) points out that often an excessive quantity of aluminum sulphate is used with tub size and expresses the opinion that it causes rapid deterioration of the paper subjected to an accelerated aging test, as well as of paper in regular use.

Richter (*15, p. 371*) calls attention to the well-known fact that acids in paper cause hydrolysis of the cellulose. He also states:

> When the hydrolysis is intensified by increase in temperature or by increase in concentration of acid reagent, the deterioration proceeds rapidly and severe embrittlement occurs.

All these writers agree that mineral acids are injurious to paper or cellulose. All work on the effect of acids on paper that has come to the attention of the writers, however, has apparently dealt exclusively with finished commercial papers that had been sized, or sized and loaded and more or less calendered. In such paper there is obviously more than one factor that may be responsible, in part at least, for deterioration. Apparently no conclusive data have been obtained through a systematic investigation on the durability as measured by folding endurance, bursting strength, and tensile strength of unloaded waterleaf paper which has been treated with definite quantities of single acids or acid salts.

EXPERIMENTAL PROCEDURE

The purposes of the investigation reported in this bulletin were: (1) To ascertain the deterioration, as indicated by loss in strength and discoloration, of waterleaf unloaded all-rag paper treated with very dilute solutions of aluminum sulphate, sulphuric acid, and hydrochloric acid; and (2) to attempt to correlate acidity with deterioration.

For this investigation 13 by 16 inch sheets of waterleaf unloaded white bond paper, all of which were made at the same time on a Fourdrinier machine in a paper mill making high-grade bond paper, were used. Each sheet was soaked in distilled water at room temperature for 15 minutes in order to remove any water-soluble substances, and then dried in air at room temperature. This paper had a relatively high folding endurance, which was not materially decreased by heating for 72 hours at 100° C. The water extract had an average pH value of 7.85. The stock was composed of new white rags in the proportion of 75 per cent linen and 25 per cent cotton. It was free from rosin and glue but contained a trace of starch. The paper weighed 21 pounds per ream of 500 sheets, 17 by 22 inches, had a thickness of 0.0045 inch, and contained 0.2 per cent ash.

The copper number was determined on 1.5 g of the ground sample by the Braidy method (*2*), which directs that the Fehlings solution be replaced by a solution of copper sulphate made alkaline with sodium carbonate and sodium bicarbonate instead of alkaline tartrate. The cuprous oxide was dissolved in molybdophosphoric reagent, and the blue solution was then titrated with standard potassium permanganate to a faint pink color as described by Gault and Mukerji (*8*).

The alpha-cellulose was determined in 5 g of the ground sample by the method described by Burton and Rasch (*3*), modified by filtering through a fritted-glass Jena crucible instead of through a cotton cloth.

The following alpha-cellulose and copper number results, calculated on moisture-free and ash-free basis, were obtained: Unheated paper, 97.2 per cent and 0.64; paper heated for 72 hours at 100° C., 96.5 per cent and 0.81.

Solutions of various strengths of chemically pure aluminum sulphate ($Al_2(SO_4)_3.18H_2O$) and sulphuric and hydrochloric acids were carefully prepared. These solutions were applied to the sheets by allowing one sheet, or subsample, folded to half its original size, to soak for 15 minutes in 500 c c of the solution. The soaking was carried on in a shallow porcelain-lined pan, and the paper was kept completely immersed in the solution during the entire period. At the end of the 15-minute period the sheet was unfolded to its original size and removed from the solution. The excess of the treating solution was shaken off by gently swinging it back and forth several times. It was then placed smooth on a glass plate and allowed to dry in a horizontal position. When dry it was cut in two equal parts. One part of each treated subsample and one untreated control were placed in an electric air oven and heated for 72 hours at 100° C. The other part of each subsample was ground fine enough in a Wiley mill (*17*) to pass through a sieve having circular holes 2 mm in diameter and then placed in sampling bottles for acidity determinations. All heated subsamples were conditioned for at least 48 hours (*13*) at 50 per cent relative humidity and 70° F. Folding endurance and tensile strength in both directions, and bursting strength tests were then made on them. Each result reported in the tables is an average of at least 10 tests. The folding endurance and tensile strength tests were made with the Schopper machines and the bursting strength with the Mullen tester.

A measure of the discoloration of the paper was also made on the heated subsamples by determining the percentage reflection of light with reference to the surface of a magnesium carbonate block. This was measured by means of a polarization photometer. The light source was a magnesium carbonate block illuminated symmetrically by two 500-watt lamps and viewed normally through a monochromatic blue filter. The paper to be tested was fastened over half the magnesium carbonate block so that it covered one-half of the field of view in the photometer. The angular setting for a match was determined three times and averaged. The paper sample and the magnesium carbonate block were then reversed, and the new angle of match was determined three times as before. The percentage reflection was then calculated by multiplying the tangent of the smaller angle of match by the cotangent of the larger angle.

Total acidity was determined by a modification of the Minor method (*16*), which directs that the titration with 0.01 normal NaOH be conducted in the presence of the ground paper. The details of the method used in this work were as follows: 1 g of the ground sample was transferred to a 200 c c pyrex glass Erlenmeyer flask, and 100 c c of carbon-dioxide-free distilled water of room temperature and having a pH value of 7 was added. One-half cubic centimeter of phenolphthalein (0.5 g dissolved in 100 c c of alcohol) was added, and a slow stream of carbon-dioxide-free air was allowed to bubble into the solution for five minutes. While a

slow bubbling of air was continued, the solution was titrated slowly with 0.01 normal NaOH until a definite pink color was permanent for at least three minutes. A correction was made for a blank determination by using water and phenolphthalein alone. All results, including those obtained on samples treated with hydrochloric acid, were calculated as parts of SO_3 per 100,000 parts of paper.

To determine the hydrogen-ion concentration, 2½ g of the ground sample was transferred to a 250 c c pyrex glass Erlenmeyer flask, and 125 c c of boiling distilled water having a pH of 7 was added. The flask was tightly stoppered and allowed to cool. The solution was then decanted off, and its pH value was determined. The electrometric method, with the quinhydrone electrode, was used for all treated samples, and the colorimetric method, with isohydric indicators adjusted in steps of 0.2 pH, was used for the untreated controls.

Total acidity and pH determination on all subsamples were made in duplicate on different days.

Each treating solution was applied to three different sheets or subsamples at different times in the manner described. In other words, the work was repeated twice. The subsamples having the suffix 1 are considered as set 1. (Tables 2, 3, and 4.) Set 2, which is represented by subsamples having the suffix 2, was not started until the heating, physical testing, and acidity determinations of set 1 were completed. Set 3, represented by subsamples having the suffix 3, was not started until set 2 was completed. This procedure of repeating the work was adopted because it was thought that the average of the triplicate sets would be more nearly correct than if each treatment were run in triplicate at the same time.

RESULTS

The effect of heating the untreated control samples of paper for 72 hours at 100° C., as shown in tests on folding endurance, bursting strength, tensile strength, and reflection of light, is recorded in Table 1. Six untreated sheets were used. Each was heated and tested separately. The effect of chemically pure aluminum sulphate and sulphuric and hydrochloric acids on folding endurance, bursting strength, tensile strength, and color of the paper artificially aged by heating for 72 hours at 100° are recorded in Tables 2, 3, and 4. The results of the triplicate sets are given separately in these tables to show the variation obtained under the same conditions of treating, heating, and testing. The effect of these chemicals on the physical properties is also expressed as percentage variation from the average strength of untreated and heated controls.

TABLE 1.—*Effect of heating for 72 hours at 100° C. on physical properties and color of untreated waterleaf all-rag bond paper*

NOT HEATED

Subsample No.	Folding endurance			Bursting strength	Tensile strength [1]			Variation from strength of unheated controls			Acidity, pH of water extract	Reflection of blue light [2]
	Transverse direction	Longitudinal direction	Average both directions		Transverse direction	Longitudinal direction	Average both directions	Folding endurance	Bursting strength	Tensile strength		
	Double folds	*Double folds*	*Double folds*	*Points*	*Kg*	*Kg*	*Kg*	*Per cent*	*Per cent*	*Per cent*		*Per cent*
1	579	2,330	1,455	37.5							7.70	83.5
2	875	2,033	1,454	35.9							7.80	87.0
3	604	2,433	1,519	37.5							8.00	83.0
4	493	2,107	1,300	37.6							7.60	85.4
5	644	1,981	1,313	39.0							8.00	88.2
6	734	2,396	1,565	35.0							8.00	86.6
Average	655	2,213	1,434	37.1	4.2	8.1	6.15				7.85	85.6

HEATED

1-1	782	2,127	1,455	38.3				0	+2.1			84.8
2-1	603	2,358	1,481	39.7				+1.9	+10.6			86.0
3-1	630	2,313	1,472	38.6				−3.1	+2.9			84.2
4-1	584	1,717	1,151	38.0				−11.5	+1.1			87.3
5-1	726	1,726	1,226	38.6				−6.6	−1.0			85.1
6-1	576	2,425	1,501	41.2				−4.1	+17.7			89.1
Average	650	2,111	1,381	39.1	4.6	8.1	6.35	−3.7	+5.4	+3.3		86.1

[1] All tensile strength tests were made on strips 15 mm wide.
[2] Discoloration is indicated by a decrease in the percentage reflection of blue light.

TABLE 2.—*Effect of aluminum sulphate on physical properties and color of waterleaf all-rag bond paper heated for 72 hours at 100° C.*

Subsample No.	Strength of $Al_2(SO_4)_3 18H_2O$	pH of treating solution	Folding endurance after heating			Bursting strength after heating
			Transverse direction	Longitudinal direction	Average both directions	
	Grams per liter		*Double folds*	*Double folds*	*Double folds*	*Points*
Heated control			650	2,111	1,381	39.1
A-1	4		0	0	0	15.3
A-2			1	1	1	20.4
A-3			0	0	0	16.6
Average	4	3.70	0	0	0	17.4
B-1	2		9	9	9	29.6
B-2			11	22	17	27.2
B-3			11	22	17	26.7
Average	2	3.90	10	18	14	27.8
C-1	1		69	150	110	31.5
C-2			78	267	173	36.0
C-3			193	286	240	39.3
Average	1	3.80	113	234	174	35.6
D-1	0.4		347	791	569	38.4
D-2			503	1,050	777	39.0
D-3			369	1,151	760	39.0
Average	.4	4.00	406	997	702	38.8
E-1	.2		387	1,762	1,075	36.8
E-2			540	1,496	1,018	38.0
E-3			395	1,449	922	38.0
Average	.2	4.20	441	1,569	1,005	37.6

TABLE 2.—*Effect of aluminum sulphate on physical properties and color of waterleaf all-rag bond paper heated for 72 hours at 100° C.*—Continued

Subsample No.	Tensile strength after heating			Variation from strength of heated controls			Acidity of unheated paper		Reflection of blue light
	Transverse direction	Longitudinal direction	Average both directions	Folding endurance	Bursting strength	Tensile strength	Total calculated as parts SO_3 per 100,000 parts paper	pH of water extract	
	Kg	*Kg*	*Kg*	*Per cent*	*Per cent*	*Per cent*			*Per cent*
Heated control	4.6	8.1	6.35					7.85	86.1
A-1				−100	−60.9		308	3.91	75.8
A-2				−99.9	−47.8		284	4.01	83.4
A-3				−100	−57.5		296	3.99	86.4
Average	2.8	5.4	4.10	−100	−55.5	−35.4	296	3.97	81.9
B-1				−99.3	−24.3		164	4.04	83.4
B-2				−98.8	−30.4		160	4.19	84.6
B-3				−98.8	−31.7		152	4.15	85.2
Average	3.7	6.8	5.25	−99.0	−28.9	−17.3	159	4.13	84.4
C-1				−92.0	−19.4		88	4.15	85.5
C-2				−87.5	−7.9		84	4.25	84.5
C-3				−82.6	+.5		84	4.24	86.6
Average	4.4	8.2	6.30	−87.4	−9.0	−.8	85	4.21	85.5
D-1				−58.8	−1.8		56	4.36	86.4
D-2				−43.7	−.3		56	4.58	86.7
D-3				−45.0	−.3		60	4.64	89.4
Average	4.3	8.3	6.30	−49.2	−.8	−.8	57	4.53	87.5
E-1				−22.2	−5.9		40	4.72	83.4
E-2				−26.3	−2.8		40	4.91	84.6
E-3				−33.2	−2.8		48	4.87	85.7
Average	4.5	8.2	6.35	−27.2	−3.8	0	43	4.83	84.6

TABLE 3.—*Effect of sulphuric acid on physical properties and color of waterleaf all-rag bond paper heated for 72 hours at 100° C.*

Subsample No.	Strength of H_2SO_4	Folding endurance after heating			Bursting strength after heating	Tensile strength after heating		
		Transverse direction	Longitudinal direction	Average both directions		Transverse direction	Longitudinal direction	Average both directions
	Grams per liter	*Double folds*	*Double folds*	*Double folds*	*Points*	*Kg*	*Kg*	*Kg*
Heated control		650	2,111	1,381	39.1	4.6	8.1	6.35
F-1	0.4904	0	0	0	10.5			
F-2		0	0	0	8.8			
F-3		0	0	0	8.0			
Average	.4904	0	0	0	9.1	1.6	2.1	1.85
G-1	.2452	8	13	11	25.2			
G-2		21	31	26	31.0			
G-3		1	1	1	25.0			
Average	.2452	10	15	13	27.1	3.3	7.0	5.15
H-1	.1226	348	984	666	39.2			
H-2		272	667	470	39.0			
H-3		198	664	431	41.0			
Average	.1226	273	772	523	39.7	4.3	8.2	6.25
I-1	.0613	465	1,548	1,007	39.4			
I-2		524	1,589	1,057	39.0			
I-3		366	1,295	831	40.0			
Average	.0613	452	1,477	965	39.5	4.4	8.2	6.30
J-1	.0306	501	1,848	1,175	38.6			
J-2		487	1,655	1,074	39.6			
J-3		499	1,709	1,104	40.7			
Average	.0306	496	1,737	1,117	39.6	4.3	8.2	6.25

TABLE 3.—*Effect of sulphuric acid on physical properties and color of waterleaf all-rag bond paper heated for 72 hours at 100° C.*—Continued

Subsample No.	Variation from strength of heated controls			Acidity of unheated paper		Reflection of blue light
	Folding endurance	Bursting strength	Tensile strength	Total calculated as parts SO_3 per 100,000 parts paper	pH of water extract	
	Per cent	*Per cent*	*Per cent*			*Per cent*
Heated control					7.85	86.1
F-1	−100.0	−73.1		104	3.65	72.2
F-2	−100.0	−77.5		74	3.95	60.6
F-3	−100.0	−79.5		84	3.76	67.2
Average	−100.0	−76.7	−70.9	87	3.79	66.7
G-1	−99.2	−35.5		69	4.11	78.7
G-2	−98.1	−20.7		52	4.28	83.0
G-3	−99.9	−36.1		60	4.16	84.0
Average	−99.1	−30.7	−18.9	60	4.18	81.9
H-1	−51.8	+.3		52	4.44	82.8
H-2	−66.0	−.3		48	4.52	86.7
H-3	−68.8	+4.9		40	4.41	84.0
Average	−62.1	+1.5	−1.6	47	4.46	84.5
I-1	−27.1	+.8		44	4.99	85.3
I-2	−23.5	−.3		36	4.75	83.0
I-3	−39.8	+2.3		32	4.64	87.5
Average	−30.1	+1.0	−.8	37	4.79	85.3
J-1	−14.9	−1.3		25	5.10	85.6
J-2	−22.4	+1.3		28	4.98	84.2
J-3	−20.1	+4.1		28	5.16	84.2
Average	−19.1	+1.3	−1.6	27	5.08	84.7

TABLE 4.—*Effect of hydrochloric acid on physical properties and color of waterleaf all-rag bond paper heated for 72 hours at 100° C.*

Subsample No.	Strength of HCl	Folding endurance after heating			Bursting strength after heating	Tensile strength after heating		
		Transverse direction	Longitudinal direction	Average both directions		Transverse direction	Longitudinal direction	Average both directions
	Grams per liter	*Double folds*	*Double folds*	*Double folds*	*Points*	*Kg*	*Kg*	*Kg*
Heated control		650	2,111	1,381	39.1	4.6	8.1	6.35
K-1	0.1823	0	0	0	14.3			
K-2		0	0	0	15.0			
K-3		0	0	0	16.2			
Average	.1823	0	0	0	15.2	2.6	5.1	3.85
L-1	.0912	3	4	4	21.1			
L-2		5	7	6	30.0			
L-3		1	2	2	22.0			
Average	.0912	3	4	4	24.4	3.5	6.5	5.00
M-1	.0456	298	740	519	36.3			
M-2		242	816	529	37.0			
M-3		325	854	590	41.0			
Average	.0456	288	803	546	38.1	4.2	8.2	6.20
N-1	.0228	490	1,678	1,084	38.3			
N-2		427	1,491	959	39.0			
N-3		505	1,855	1,180	39.0			
Average	.0228	474	1,675	1,075	38.8	4.3	8.3	6.30

TABLE 4.—*Effect of hydrochloric acid on physical properties and color of waterleaf all-rag bond paper heated for 72 hours at 100° C.*—Continued

Subsample No.	Variation from strength of heated controls			Acidity of unheated paper			Reflection of blue light
				Total calculated as—			
	Folding endurance	Bursting strength	Tensile strength	Parts HCl per 100,000 parts paper	Parts SO_3 per 100,000 parts paper	pH of water extract	
	Per cent	*Per cent*	*Per cent*				*Per cent*
Heated control						7.85	86.1
K-1	−100.0	−63.4		47	52	4.24	81.0
K-2	−100.0	−61.6		51	56	4.39	78.6
K-3	−100.0	−58.6		33	36	4.45	85.2
Average	−100.0	−61.1	−39.4	44	48	4.36	81.6
L-1	−99.7	−46.0		36	39	4.37	83.1
L-2	−99.6	−23.3		40	44	4.44	85.7
L-3	−99.9	−43.7		44	48	4.47	83.6
Average	−99.7	−37.6	−21.3	40	44	4.43	84.1
M-1	−62.4	−7.2		36	39	4.66	85.5
M-2	−61.7	−5.4		35	38	4.68	83.1
M-3	−57.3	+4.9		31	34	4.68	85.8
Average	−60.5	−2.6	−2.4	34	37	4.67	84.8
N-1	−21.5	−2.0		29	32	4.86	87.0
N-2	−30.6	−.3		33	36	4.92	83.7
N-3	−14.6	−.3		26	29	5.04	87.3
Average	−22.2	−.8	−.8	29	32	4.94	86.0

The total acidity figures are given as parts of SO_3 per 100,000 parts of paper, the pH figures are values obtained on the water extract of the paper, and the percentage reflection of light is a measurement of the change in color of the sample.

Figure 1 shows the effect of the chemicals used on folding endurance of the paper heated for 72 hours at 100° C. Figures 2 and 3 show the effect of the same chemicals on the bursting strength and tensile strength. Only the average results of the triplicate sets are shown in the graphs.

DISCUSSION OF RESULTS

As the results obtained on the three sets of samples treated at different times with the same solution are in fairly good agreement with respect to the effect on the folding endurance, bursting strength, and tensile strength, only the average of the three sets given in the tables and graphs are considered in this discussion.

Where the pH of the water extract of the paper treated with aluminum sulphate, sulphuric acid, or hydrochloric acid is plotted against the percentage decrease in folding endurance (fig. 1), the curves show that the papers which were treated with aluminum sulphate and sulphuric acid and which yielded water extracts of the same pH value suffered essentially the same deterioration, whereas those treated with hydrochloric acid were subject to de-

cidedly greater deterioration for the same pH of the water extract when the pH of the extract was below 4.80.

Where the total acidity values are plotted against the percentage loss in folding endurance, bursting strength, and tensile strength (figs. 1, 2, and 3), the curves show that hydrochloric acid causes a greater deterioration than does sulphuric acid, whereas the total titratable acidity of aluminum sulphate, as was to be expected, is not nearly so harmful to the paper as is the equivalent quantity of free sulphuric acid.

UNTREATED CONTROL

Table 1 shows that the pH of the water extract of the six sheets of untreated paper ranged from 7.60 to 8 and averaged 7.85.

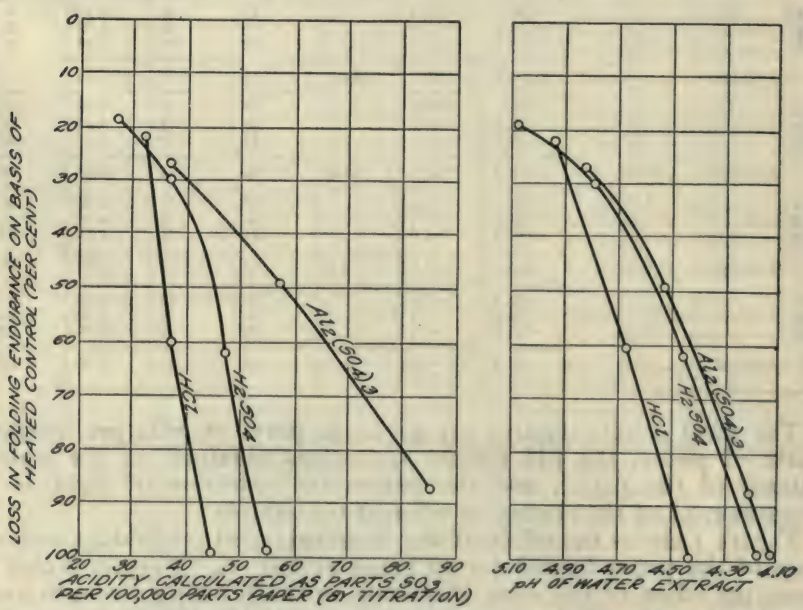


FIGURE 1.—Effect of $Al_2(SO_4)_3$, H_2SO_4, and HCl on folding endurance of waterleaf paper heated for 72 hours at 100° C.

The untreated control sheets showed practically no change in folding endurance, bursting strength, or tensile strength after being artificially aged by heating from 72 to 336 hours at 100° C.

The average folding endurance of the unheated controls was 1,434 double folds, the average tensile strength was 6.15 kg, and the average bursting strength was 37.1 points. After the paper was heated at 100° C. for 72 hours the average folding endurance, tensile strength, and bursting strength were 1,381 double folds, 6.35 kg, and 39.1 points. Paper heated for 336 hours had a folding endurance of 1,338 double folds, a tensile strength of 6.25 kg, and a bursting strength of 40.5 points.

Heating for 72 hours caused no perceptible change in the color of the untreated paper. The percentage of light reflected by the unheated controls ranged from 83 to 88.2, averaging 85.6, and the

heated controls ranged from 84.2 to 89.1, averaging 86.1, which is practically the same as for the unheated controls.

Table 1 also shows the variation in folding endurance and bursting strength that may be expected between the various sheets of paper used in the experiments. The average folding endurance of the unheated controls ranged from 1,300 double folds on subsample 4 to 1,565 double folds on subsample 6, and the bursting strength ranged from 35 points on subsample 6 to 39 points on sub-

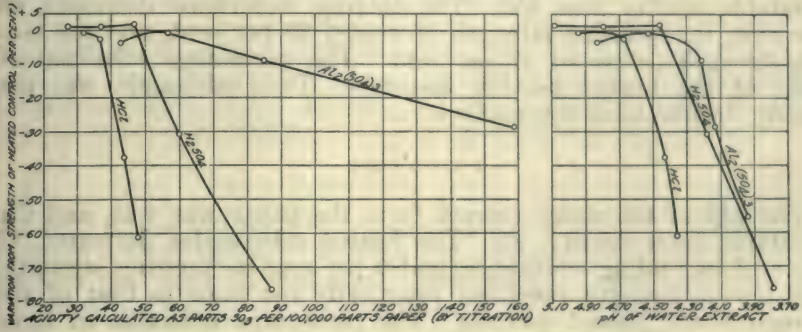


FIGURE 2.—Effect of $Al_2(SO_4)_3$, H_2SO_4, and HCl on bursting strength of waterleaf paper heated for 72 hours at 100° C.

sample 5. The variation between the heated portions of the same sheets was about the same as that of the unheated portion. The average folding endurance of the heated controls ranged from 1,151 double folds on subsample 4–1 to 1,501 on subsample 6–1, and the bursting strength ranged from 38 points on subsample 4–1 to 41.2 on subsample 6–1.

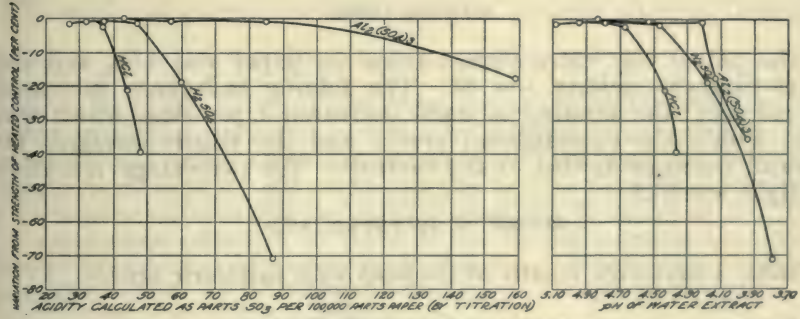


FIGURE 3.—Effect of $Al_2(SO_4)_3$, H_2SO_4, and HCl on tensile strength of waterleaf paper heated for 72 hours at 100° C.

EFFECT OF ALUMINUM SULPHATE

The results of the tests with aluminum sulphate are shown in Table 2.

4 G PER LITER

The average pH value of the water extract from the subsamples treated with a 0.4 per cent solution of $Al_2(SO_4)_3 \cdot 18H_2O$ was 3.97, and the total titratable acidity was 296. On artificial aging by heating for 72 hours at 100° C, the folding endurance decreased

100 per cent, the bursting strength decreased 56 per cent, and the tensile strength decreased 35 per cent. The percentage reflection of light of the heated portion was 81.9. This subsample was slightly darker than the untreated and heated controls.

2 G PER LITER

The pH of the water extract from the paper was 4.13; the total titratable acidity was 159. The folding endurance decreased 99 per cent, the bursting strength decreased 29 per cent, and the tensile strength decreased 17 per cent. The percentage reflection of light of the heated portion was 84.4. This subsample was not visibly darker than the controls.

1 G PER LITER

The pH of the water extract from the paper was 4.21, and the titratable total acidity, 85. The heated subsamples decreased 87 per cent in folding endurance, and 9 per cent in bursting strength. The tensile strength remained practically the same as that of the untreated and heated controls. The percentage reflection of light was 85.5, or practically the same as that of the controls.

0.4 G PER LITER

The pH of the water extract from the paper was 4.53, and the total titratable acidity was 57. The folding endurance decreased 49 per cent, but the bursting strength, tensile strength, and reflection of light remained practically the same as those of the controls.

0.2 G PER LITER

The pH of the water extract from the paper was 4.83, and the total titratable acidity was 43. The folding endurance decreased 27 per cent; the bursting strength decreased 4 per cent, which was well within the experimental error; and the tensile strength remained the same as that of the controls. The percentage reflection of light was 84.6.

EFFECT OF SULPHURIC ACID

Table 3 shows the results of the tests with sulphuric acid.

0.4904 G PER LITER (0.01 N.)

The average pH of the water extract from the subsamples treated with sulphuric acid was 3.79, and the total titratable acidity was 87. The folding endurance decreased 100 per cent, the bursting strength decreased 77 per cent, and the tensile strength decreased 71 per cent when the paper was heated for 72 hours at 100° C. The percentage reflection of light of the heated portion was 66.7. This portion was considerably darker than the untreated and heated controls.

0.2452 G PER LITER (0.005 N.)

The pH of the water extract from the paper was 4.18, and the total titratable acidity was 60. The folding endurance decreased 99 per cent, the bursting strength decreased 31 per cent, and the tensile strength decreased 19 per cent upon heating for 72 hours at 100° C. The percentage reflection of light of the heated portion was 81.9. This subsample was slightly darker than the controls.

0.1226 G PER LITER (0.0025 N.)

The pH of the water extract from the paper was 4.46, and the total titratable acidity was 47. The decrease in folding endurance was 62 per cent, but the bursting strength, tensile strength, and reflection of light remained practically the same as those of the controls.

0.0613 G PER LITER (0.00125 N.)

The pH of the water extract from the paper was 4.79, and the total titratable acidity was 37. The folding endurance decreased 30 per cent, but the bursting strength, tensile strength, and reflection of light remained practically the same as those of the controls.

0.0306 G PER LITER (0.000625 N.)

The pH of the water extract from the paper was 5.08, and the total titratable acidity was 27. The decrease in folding endurance was 19 per cent, but the bursting strength, tensile strength, and reflection of light remained about the same as those of the controls.

EFFECT OF HYDROCHLORIC ACID

The results of the tests with hydrochloric acid are given in Table 4.

0.1823 G PER LITER (0.005 N.)

The average pH value of the water extract from the subsamples treated with this solution was 4.36, and the total titratable acidity was 48. The folding endurance decreased 100 per cent, the bursting strength decreased 61 per cent, and the tensile strength decreased 39 per cent upon artificial aging by heating for 72 hours at 100° C. The percentage reflection of light of the heated portion was 81.6. This subsample was slightly darker than the untreated and heated controls.

0.0912 G PER LITER (0.0025 N.)

The pH of the water extract from the paper was 4.43, and the total titratable acidity was 44. The folding endurance decreased 100 per cent, the bursting strength decreased 38 per cent, and the tensile strength decreased 21 per cent. The heated paper showed no visible discoloration, the reflection of light being 84.1 per cent.

0.0456 G PER LITER (0.00125 N.)

The pH of the water extract from the paper was 4.67, and the total titratable acidity was 37. The folding endurance decreased 61 per

cent. The bursting strength, tensile strength, and reflection of light remained practically the same as those of the controls.

0.0228 G PER LITER (0.000625 N.)

The pH of the water extracts from the paper was 4.94, and the total titratable acidity was 32. The decrease in folding endurance was 22 per cent, and the bursting strength, tensile strength, and reflection of light remained practically the same as those of the controls.

CONCLUSIONS AND SUMMARY

Experiments were conducted to show the effect of small quantities of aluminum sulphate and sulphuric and hydrochloric acids on the folding endurance, bursting strength, tensile strength, and color of waterleaf all-rag bond paper artificially aged by heating for 72 hours at 100° C.

The folding endurance, bursting strength, tensile strength, and color of the untreated paper heated for 72 hours at 100° C. remained essentially the same as those for the unheated paper. The differences that occurred in these experiments are within the limits of error of the method of test.

Small quantities of aluminum sulphate, sulphuric acid, or hydrochloric acid in paper caused its rapid deterioration. The deterioration increased as the quantities of these chemicals were increased. Hydrochloric acid caused greater and more rapid deterioration than did sulphuric acid or aluminum sulphate when the pH values of the water extract or the total titratable acidity were the same.

When the pH of the water extract from the paper treated with these chemicals was 5.10, the loss in folding endurance on heating was less than 20 per cent. By extrapolation it appears that the loss at a pH of 5.50 would be approximately 10 per cent.

When the total titratable acidity of the paper was less than 20 (calculated as parts SO_3 per 100,000 parts paper), the loss in folding endurance of the heated paper was less than 20 per cent.

When the pH of the water extract from the paper treated with aluminum sulphate, sulphuric acid, or hydrochloric acid was greater than 4.20, 4.40, and 4.60, respectively, the loss in bursting strength on heating was less than 10 per cent.

When the total titratable acidity of the paper treated with aluminum sulphate, sulphuric acid, or hydrochloric acid was less than 85, 50, and 38, respectively, the loss in bursting strength of the heated paper was less than 10 per cent.

When the pH of the water extract from the paper treated with aluminum sulphate, sulphuric acid, or hydrochloric acid was greater than 4.20, 4.30, and 4.55, respectively, the loss in tensile strength of the treated paper was less than 10 per cent.

When the total titratable acidity of the paper treated with aluminum sulphate, sulphuric acid, or hydrochloric acid was less than 135, 55, and 40, respectively (calculated as parts SO_3 per 100,000 parts paper), the loss in tensile strength of the heated paper was less than 10 per cent.

The folding endurance, bursting strength, and tensile strength rapidly and progressively decreased as the pH value of the water

extracts of the treated samples decreased from the figures given in the preceding paragraphs, and as the total titratable acidity increased from the figures given above.

The folding endurance of the paper was decidedly more affected by acidity, whether expressed as pH of the water extract or as total titratable acidity, than was the bursting strength or the tensile strength.

Of the three tests employed, folding endurance yielded the most significant results as to the effect of mineral acids on this paper. It appears to be the only one of the three necessary to make in studying the deterioration of paper by acids.

An observable discoloration of this paper occurred on heating (1) when it contained sufficient aluminum sulphate to give a water extract having a pH of about 3.95, (2) when it contained sufficient sulphuric acid to give a water extract having a pH of about 4.15, or (3) when it contained sufficient hydrochloric acid to give a water extract having a pH of about 4.35. The paper containing these chemicals and having a pH somewhat higher than these figures showed no visible discoloration, whereas the paper having a pH value somewhat less than these figures showed a pronounced discoloration.

Although no relation has been established between the deterioration of paper under the experimental and actual service conditions, it seems reasonable to assume that in general such a relation exists. Acids and acid salts, even in the small proportions used in these experiments, exert a slow deteriorating effect on paper, which may not be observable for many years.

LITERATURE CITED

(1) Baker, W. E. B.
1930. relationship of impurities to paper permanence. Paper Trade Jour. 91 (4): 51–52.

(2) Braidy, H.
1921. influence, sur l'indice de cuivre des cotons, des diverses circonstances ouib ont regi le chlorage. Rev. Gen. Mat. Color. 25: 35–42, illus.

(3) Burton, J. O., and Rasch, R. H.
1931. the determination of the alpha-cellulose content and copper number of paper. U. S. Dept. Com., Bur. Standards Jour. Research 6: 603–619, illus.

(4) Coward, H. F., Wood, F. C., and Barrett, F. L.
1923. the tendering of cotton fabric by acids. Jour. Textile Inst. 14: T520–T528, illus.

(5) Edlund, T.
1910. schwefelsäure im papier. Papier Fabrik. 8: 765–766.

(6) Evans, J., Chairman.
1898. report of the committee on the deterioration of paper. Jour. Soc. Arts 46: 597–601.

(7) Feichtinger.
1882. the cause of the acid reaction in many qualities of paper. Dingl. Polyt. Jour. 245: 174. [Original not seen. Abstract in Jour. Soc. Chem. Indus. I: 380. 1882.]

(8) Gault, H., and Mukerji, B. C.
1924. sur la détermination des indices de cuivre des matières cellulosiques. Application di la méthode molybdomanganimétrique de fontès thivolle. Compt. Rend. Acad. Sci. [Paris] 178: 711–713.

(9) Hall, G.
1926. permanence of paper. Paper Trade Jour. 82 (14): 52–58, illus.

(10) HERZBERG, W.
1895. DIE AUSDAUERFÄHIGKEIT UNSERER PAPIERE. Chem. Indus. Ztschr. 18: 476–479.
(11) HOFFMAN, W. F.
1928. EFFECT OF RESIDUAL ACID ON RATE OF DETERIORATION OF PAPER. Paper Trade Jour. 86 (9): 58–60, illus.
(12) ———
1929. DETERIORATION OF PAPER BY EXCESSIVE ACIDITY. Paper Trade Jour. 88 (12): 59–60.
(13) JARRELL, T. D.
1927. EFFECT OF ATMOSPHERIC HUMIDITY ON THE MOISTURE CONTENT OF PAPER. Paper Trade Jour. 85 (3): 47–51, illus.
(14) LESTER, J. H.
1915. THE ACID "TENDERING" OF COTTON CLOTH. Jour. Soc. Chem. Indus. 34: 934–936.
(15) RICHTER, G. R.
1931. DURABILITY OF PURIFIED WOOD FIBERS. ACCELERATED AGING TESTS OF VARIOUS TYPES OF PAPER-MAKING FIBERS. Indus. and Engin. Chem. 23: 371–380, illus.
(16) WEHMER, P. F., Chairman
1931. METHODS OF DETERMINING ACIDITY IN PAPER. REPORT OF SUBCOMMITTEE ON PAPER TESTING CHEMICAL METHODS. Paper Trade Jour. 92 (16): 63–64.
(17) WILEY, S. W.
1925. A NEW LABORATORY MILL. Indus. and Engin. Chem. 17: 304, illus.
(18) WINKLER, O.
1903. VERHALTEN DER MINERALSÄUREN IM PAPIER UND IHRE WIRKUNG AUF DIE FASERSTOFFE. Ztschr. Angew. Chem. 16: 25–27.
(19) WURSTER, C.
1888. PAPER TESTING. Papier Ztg. 13: 411. [Original not seen. Abstract in Jour. Soc. Chem. Indus. 7: 338. 1888.]

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - Price 5 cents

TECHNICAL BULLETIN No. 333 OCTOBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE

WASHINGTON, D. C.

FOOD SUPPLY AND PELLAGRA INCIDENCE IN 73 SOUTH CAROLINA FARM FAMILIES

By HAZEL K. STIEBELING, *Senior Food Economist, Economics Division*, and HAZEL E. MUNSELL, *Senior Nutrition Chemist, Foods and Nutrition Division, Bureau of Home Economics* [1]

In Cooperation With the South Carolina Extension Service and the South Carolina State Board of Health

CONTENTS

	Page
Introduction	1
Scope and method of study	2
Classification of families	3
Physical examinations	5
Food-consumption data collected	6
Methods of evaluating food-consumption data	7
Method of calculating money value of food used	10
Food supply of unaided families	10
Complete dietary records over short periods	11
Use of specified food materials in relation to incidence of pellagra	14
Food selection in relation to money value of diets	16
Use of supplementary foods in relation to incidence of pellagra among aided families	18
Dry skim milk	18
Evaporated milk	19
Wheat germ	19
Cured lean pork	19
Canned tomatoes	19
Pure dried yeast	20
General observations	20
Incidence of pellagra in relation to sex and age	21
Suggestions for improving diets	21
Summary and conclusions	22
Appendix	23
Literature cited	34

INTRODUCTION

The food resources of the United States are capable of providing abundantly for the population, yet the diets of many families are inadequate for maintaining full physical well-being. Proper food can make the difference between average and better-than-average vigor. Dietary deficiencies lower the resistance of the body to disease, retard growth or permit imperfect development, impair health, and shorten the duration of the prime of life. When the diet is very inadequate, dietary deficiency diseases may appear.

Pellagra is one of these diseases. It occurs among both farming and wage-earning families who use a certain type of poorly balanced

[1] The authors wish to acknowledge the contributions of Edith Hawley, formerly of the Bureau of Home Economics, who initiated, planned, and directed the study in the spring of 1929. Acknowledgment is also due to Evelyn de Medici, Lonny Landrum, Minnie Floyd, Reba Sheppard, and Sally Pearce of the South Carolina Extension Service, who assisted in securing the necessary cooperation and in collecting the data; to Madge Vaughn, a fellow of the University of South Carolina, who assisted in the field work and in summarizing the data; to S. B. Du Bose and H. M. McLure, of Lee County, to A. B. Hooton, of Darlington County, to A W. Humphries, of Kershaw County and to J. B. Setzler, of Richland County, who made the physical examinations of the families.

128705°—32——1

diet composed mainly of highly milled cereals, sweets, and lard or salt pork. Subsistence for several months or even for shorter periods on this one-sided diet leads to the development of pellagra. This disease occurs not because these foods are unwholesome in themselves but because, when they are eaten to the exclusion of all others, they form a diet which does not furnish the body with enough of certain necessary food factors. The pellagra-preventing factor is fairly abundant in milk, lean meat, and fish; sparingly present in most vegetables, and quite lacking in highly refined flour and cereals, in fats, and in sugar. Studies of the United States Public Health Service still in progress indicate not only the kinds of food which are pellagra preventing, but also the approximate amount of each needed to prevent the disease when the rest of the diet is very deficient in the pellagra-preventing vitamin. Rarely, however, are pellagra-producing family dietaries inadequate in the pellagra-preventing vitamin only; usually they are also very deficient in other vitamins, in iron, and in protein, especially protein from animal sources.

It has been estimated (*19*)[2] that about 200,000 persons in the United States had suffered from pellagra in 1929. These cases occurred mainly in the South, among low-income groups. In some instances ignorance of food values and faulty food habits were probably responsible for the condition, and in others an economic situation which put an adequate diet beyond reach. In addition to factors outside the control of the families affected, the difficulties of the situation were often intensified by the failure to use to advantage the money available for food, or to make wise use of the land available for home food production.

The situation calls for widespread educational work among such families. Improvement of their standard of living depends on knowledge on the part of the people themselves, and on their opportunity to obtain food which is not only pellagra preventing but adequate in all other respects.

In order to make recommendations as to diet for any community it is necessary to have definite information on the kind and quantity of food customarily used and on the prevailing practices in home food production and conservation. Under some circumstances it is also necessary to conduct a health survey. In 1929–30 the Bureau of Home Economics and the South Carolina Extension Service undertook studies to secure such information from farm families in a section of South Carolina where pellagra was prevalent.

SCOPE AND METHOD OF STUDY

The investigation included the collection of information regarding the food used by 73 farm families in Lee County, S. C.; the evaluation of the food supply in terms of its adequacy for good nutrition; periodic examinations of members of the cooperating families for symptoms of pellagra; and a study of the relation of the food supply to pellagra incidence.

The food habits of the families successful in warding off pellagra, as well as those of the families succumbing to the disease, were carefully observed, and nutrition demonstrations were conducted in which pellagra-preventing food materials were furnished to certain families.

[2] Italic numbers in parentheses refer to Literature Cited, p. 34.

The findings include facts regarding the character of the customary diets which were pellagra preventing, and regarding the effectiveness for health protection of adding definite quantities of selected pellagra-preventing food materials to the nonpellagra-preventing diets. This information affords a sound basis for dietary recommendations for families in Lee County and in other sections where similar conditions prevail.

CLASSIFICATION OF FAMILIES

The cooperation of the 73 farm families included in the study was secured by field agents who were local home demonstration agents engaged in the Cooperative Extension Service of South Carolina and of the United States Department of Agriculture. The families were divided by the field agents into two groups: (1) Families in a very unsatisfactory economic situation, members of which were suffering from pellagra at the time, or whose health history and estimated food supply were such that it seemed likely they would succumb to pellagra during the late spring. This group consisted of 44 families. To each of these families some one kind of pellagra-preventing food material was furnished in definite quantities for known periods previous to May or June. The food materials provided were dry skim milk, evaporated milk, wheat germ, cured lean pork, canned tomatoes, and pure dry yeast; (2) families whose economic condition indicated that without aid they could probably furnish themselves with some of the pellagra-preventing foods, and thus maintain a better state of nutrition than their neighbors could if unaided. Twenty-nine families composed this group. Throughout the period of observation these families depended solely on their own resources for their food supply. Subsequent records showed, however, that the field agents had overestimated the importance of the food resources of some of these families. In 15 of them some one or more members incurred pellagra during the late spring.

Twenty-six families, of which 19 received aid in the form of food, cooperated in this investigation during the spring of 1929; the remaining 47, of which 25 received such aid, cooperated during the fall and winter of 1929 and the spring of 1930.

The number and size of all of the families cooperating in this investigation are shown in Tables 1 and 14. Those receiving aid are classified according to the kind of food which they received; and those not receiving aid, according to the pellagra-preventing character of their food as judged by the incidence of pellagra among them in the late spring of the year of the study. The groups of families were, on the average, similar in family size and composition.

TABLE 1.—*Average size and composition, by age groups, of families depending on their own resources for food, classified by type of diet used throughout the year, and of aided families classified by the kind of supplementary food received*

Classification	Families cooperating	Family size	Members of family in age group of—		
			18 years and over	11 to 17 years	Under 11 years
Unaided families whose food supply was—	*Number*	*Persons*	*Persons*	*Persons*	*Persons*
Pellagra preventing throughout the year	14	6.64	2.50	1.50	2.64
Not pellagra preventing throughout the year	15	6.33	2.60	1.60	2.13
Total or average	29	6.48	2.55	1.55	2.38
Aided families whose food supply was supplemented with—					
Dry skim milk	13	6.53	2.23	1.38	2.92
Evaporated milk	14	6.21	2.36	1.21	2.64
Wheat germ	7	7.28	2.57	2.00	2.71
Lean cured pork	6	3.34	2.00	.67	.67
Canned tomatoes	2	7.00	2.50	1.00	3.50
Yeast	2	8.00	2.50	3.00	2.50
Total or average	44	6.21	2.32	1.39	2.50

Tables 2, 3, and 14 give some facts regarding the health history, the type of land tenure, and the food resources of all cooperating families. About two-thirds of the unaided families and four-fifths of the aided families reported a history of pellagra. About half of the unaided families were farm owners; most of the aided families were tenants. Although pellagra has often been associated with the tenant type of agriculture, the type of land tenure seems to have had little relation to the reported history of the occurrence of pellagra in so far as this study is concerned. The disease had previously occurred in 13 of the 18 farm-owning families and in 43 of 55 tenant families.

TABLE 2.—*Type of land tenure and reported family history of pellagra of all cooperating families*

Classification	Families cooperating			Families reporting history of pellagra		
	Total	Farm owners	Tenants, croppers, hired men	Total	Farm owners	Tenants, croppers, hired men
Unaided families whose food supply was—	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
Pellagra preventing throughout the year	14	9	5	6	5	1
Not pellagra preventing throughout the year	15	5	10	12	5	7
Total	29	14	15	18	10	8
Aided families whose food supply was supplemented with—						
Dry skim milk	13	1	12	12	1	11
Evaporated milk	14	0	14	13		13
Wheat germ	7	3	4	5	2	3
Cured lean pork	6	0	6	6		6
Canned tomatoes	2	0	2	1		1
Pure dry yeast	2	0	2	1		1
Total	44	4	40	38	3	35

TABLE 3.—*Food resources of all cooperating families reported for winter, 1928–29 or 1929–30*

Classification	Families cooperating	Families reporting possession of—					
		Cows	Hogs	Poultry flock		Vegetable garden	Dried beans or peas for winter use
				For meat	For eggs		
Unaided families whose food supply was—	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
Pellagra preventing throughout the year	14	11	10	7	10	11	9
Not pellagra preventing throughout the year	15	3	10	8	8	10	10
Total	29	14	20	15	18	21	19
Aided families whose food supply was supplemented with—							
Dry skim milk	13	3	6	10	8	7	11
Evaporated milk	14	1	9	6	6	5	4
Wheat germ	7	2	3	5	3	4	3
Cured lean pork	6	3	0	3	5	3	0
Canned tomatoes	2	1	2	0	2	0	2
Pure dry yeast	2	0	2	1	1	1	0
Total	44	10	22	25	25	20	20

The use made of the land rather than the type of land tenure is the important matter. Eleven of the 14 families which had a pellagra-preventing diet while depending on their own resources for food secured it by devoting part of their land to the support of milk cows, swine, poultry, and gardens. Aside from the milk supply, however, the food resources of the unaided group during the study were not very different from those of other cooperating families. The aided families, on the whole, reported food resources somewhat less abundant than those of the unaided families whose food was found to be not pellagra preventive. Pellagra incidence during the period of the study among the various aided groups may, therefore, be contrasted with that among the unaided families whose food was not pellagra preventive, in order to determine the effect of the supplementary food.

PHYSICAL EXAMINATIONS

Data were obtained on pellagra incidence during this study by means of physical examinations made of the members of each family in the presence of the field workers. These examinations were made by county health doctors cooperating with the South Carolina State Board of Health. Usually the same physician examined the same families at each successive examination. Unfortunately, from the standpoint of this investigation, every member of each household could not be present for each examination; therefore only the records of those individuals examined periodically are included in this report.

The condition diagnosed as pellagra by the cooperating physicians was that described by Goldberger (*3*). Loss of strength with indigestion or nervousness, or both, appearing or increasing in the late winter or spring, and lessening or disappearing in the fall, weariness, dizziness or vertigo, discomfort or pain in the pit of the stomach, headache, wakefulness, and frequently also sluggish bowel action are common early symptoms of the disease. Such symptoms may of

course be due also to causes other than pellagra. A burning of the mouth, reddened tongue, and burning of the hands and feet may be characteristics of later stages of pellagra, and their presence justified a suspicion of the disease, especially if the individual was known to use a diet low in milk, meat, vegetables, and fruit. The most definite and distinctive signs of the disease are skin lesions, more or less bilaterally symmetrical, appearing at first like sunburn, then turning a dirty brown color with parchmentlike texture; later the skin becomes rough and scaly and even cracks and peels. The eruption appears most frequently on the backs of the hands, on the feet, forearms, legs, neck, and back. In children, such symptoms as listlessness and fretfulness, loss of activity, and loss of weight may be detected early, but these preliminary indications often escape notice until the appearance of the characteristic eruption.

The members of families cooperating in the part of the study made in the spring of 1929 were given two physical examinations, one in April (Apr. 12 to 14) and the other after the middle of June (June 22 to 25). May and June are months in which the incidence of pellagra approaches a peak. The first examination of the families cooperating the following fall and spring was made during the latter part of November, 1929, at which time information was secured regarding the history of pellagra in the family. The second examination of this group was made in February, 1930, and a third during the last 10 days in May. A final examination was given certain families in the fall of 1930, at which time inquiry was made as to attacks of pellagra beginning after the May examination.

FOOD-CONSUMPTION DATA COLLECTED

Three types of information on the food supply were obtained from every family. These included (1) statements of the provision made for the winter food, (2) complete records of the kinds and quantities of food used over short periods, and (3) records of the use of specified foods over relatively long periods in the spring.

The information as to the provision made by each family for a winter food supply of milk, pork, poultry, eggs, and dried peas was obtained by the investigators in order to help decide which families most needed supplementary food and which kind should be given.

To secure complete data on the type of food customarily used by the cooperating families, records of total food consumption for one week were obtained in April from families who cooperated in the spring of 1929. Similar records of the food used in one week during the latter part of November, 1929, and again in two weeks during April or the early part of May, 1930, were secured from families cooperating in the fall of 1929 and in the spring of 1930. The records consisted of inventories, taken with the help of the investigators, of the food on hand at the beginning and at the end of these periods, of records kept by the housewife of food purchased in the meantime or brought in from the farm, and of records of the edible food given to animals or pets, or used for purposes other than family consumption. Data on the number and ages of the persons nourished by this food were also obtained.

Since the keeping of dietary records is exacting, it was found impossible to secure them from all of the cooperating families. Only a small number kept them for both fall and spring periods. Some of

the records which were secured bore internal evidence of inaccuracy, and all such data have been excluded from this report. Records which could be used were obtained from 7 families in April, 1929, from 18 families in November, 1930, and from 15 of the latter group and from 4 additional families in April or early May, 1930. These 44 records were all received from the 29 families which did not receive aid.

The onset of pellagra may not occur until a diet deficient in pellagra-preventive food materials has been used for several weeks or even several months. Hence it seemed important to accumulate information on the quality of the diet of the cooperating families over a long period in the late winter and early spring, this being a time when farm diets are likely to be restricted in variety and perhaps also in quantity. With the limited amount of time at the disposal of the investigators, it was impossible to obtain complete records of all the food used over a period of several months. Records were therefore made by the housewife and collected every two weeks by the investigators to show the quantities of dairy products, lean meat, fruits, and vegetables used daily to supplement the flour or meal, fats, and sweets which form the bulk of the customary diets.

METHODS OF EVALUATING FOOD-CONSUMPTION DATA

The data obtained regarding the total food used by the cooperating families over the short periods have been analyzed (1) in terms of the quantities of the various articles of food used, (2) in terms of the fuel value and the quantities of certain nutrients obtained from the food, and (3) in terms of the percentage of calories derived from specified types of food.

The records of the use of certain specified food materials over long periods in the spring have been analyzed only in terms of quantities used per person per day.

FOOD COMPOSITION

The nutritive value of the food supply has been calculated in terms of calories, grams of protein, calcium, phosphorus and iron, and units of certain vitamins. Figures on the average nutritive values of common food materials were compiled from various sources, but mainly from Atwater and Bryant (*1*), from Rose (*18*), and from Sherman (*20*). Calculated values of 0.327 per cent of calcium and 0.555 per cent of phosphorus were used in estimating these elements in the self-rising white flour. Figures for vitamins A and C were taken from tables issued by the New York Association for Improving the Condition of the Poor (*16*) and those for the pellagra-preventing factor were calculated from data given in publications of the United States Public Health Service (*5, 6, 8, 9, 10, 11, 12, 13, 23*). A value of unity was assigned to that quantity of each food material which Goldberger and his collaborators found to be preventive of pellagra in man when given in addition to diets lacking pellagra-preventing value.

FAMILY EQUIVALENTS

When dealing with groups which are nonhomogeneous so far as nutritional needs are concerned, it is obviously incorrect to compare directly the total value of the food used by individual families or

groups of families, or to compare even per capita figures. Not only do family groups differ in the number of members, but the members differ from each other in age, size, and activity. Some device must be employed to weight the relative nutritional needs of persons of varying age, size, and activity so that the relative needs of various family groups may be reduced to common terms. In this study the relative needs of each individual for energy (calories), protein, calcium, phosphorus, and iron have been expressed in terms of the allowances made for an adult man at moderate muscular work, i. e., 3,000 calories, 67 grams of protein, 0.68 gram of calcium, 1.32 grams of phosphorus, and 0.015 gram of iron. Table 4 indicates the factors by which these standard allowances can be converted into allowances for persons of various ages and activities.

TABLE 4.—*Factors expressing the relative allowance of calories and nutrients for individuals, by age, sex, and activity groups*

[Unity represents 3,000 calories, 67 grams of protein, 0.68 gram of calcium, 1.32 grams of phosphorus, and 0.015 gram of iron]

Group, by sex, age, and muscular activity	Factors expressing relative allowances of—				
	Calories	Protein	Calcium	Phosphorus	Iron
Male, 18 to 60 years, moderately active	1.0	1.0	1.0	1.0	1.0
Child:					
Under 4 years	.4	.7	1.5	.7	.4
4 to 8 years	.6	.9	1.5	.8	.6
9 to 11 years	.7	1.1	1.5	.9	.8
12 to 15 years	.9	1.2	1.4	1.0	1.0
Male:					
16 to 17 years	1.1	1.3	1.2	1.0	1.0
18 to 60 years, active	1.2	1.1			
18 to 60 years, moderately active	1.0	1.0			
18 to 60 years, sedentary	.8	1.0	1.0	1.0	1.0
60 years and over, moderately active	.9	.9			
60 years and over, sedentary	.8	.9			
Female:					
16 to 17 years	.8	.9	1.2	1.0	1.0
18 to 60 years, active	.9	.9			
18 to 60 years, moderately active	.8	.8			
18 to 60 years, sedentary	.7	.8	1.0	1.0	1.0
60 years and over, moderately active	.7	.7			
60 years and over, sedentary	.6	.7			

By the use of the factors given in Table 4, five sets of "adult units" can be calculated for each family, one for each food essential for which dietary standards have there been assigned. The calculated nutritive values of any dietary expressed in terms of chemical composition on an adult-unit basis may then be compared with the standards cited for the adult.

STANDARDS OF DIETARY ADEQUACY

Unity in Table 4 represents the standard allowances for an adult man weighing 154 pounds and engaged in moderately active work (*20*). These allowances for protein and the specified mineral elements are each 50 per cent higher than the average minimum requirements for the maintenance of nutritional equilibrium.

These standards and factors indicating equivalency do not interpret the relative need of the various members of the family for all of the food substances necessary for normal nutrition. They include only

those for which there is knowledge of the approximate quantities needed by the body, and of the approximate quantities furnished by common American food materials, and of which some American dietaries contain less than would appear to constitute a wise margin of safety.

In calculating the number of adult units in the farm families included in this study, a factor of 1.2 has been used as the energy equivalent for the men and 0.9 for the women from 18 to 60 years of age, because these members of the family were engaged in work which required more than moderate muscular activity for its performance. The use of factors greater than unity for any nutrient has the advantage of permitting direct comparison of the data with the standards set for a man at moderate muscular work, but it has the disadvantage of permitting the less critical reader to underestimate the total amount of any nutrient used by the family group. The finding that a family has used 3,300 calories per adult unit per day, for example, means that the standard of 3,000 calories was exceeded by 10 per cent, and that enough food was reported as used to furnish the active adult man (factor for energy, 1.2) with 3,960 calories; the active adult woman (factor for energy, 0.9) with 2,970 calories; and other members of the family group with 10 per cent more than the allowances indicated by Table 4.

It is recognized that food may not be distributed at the family table among individuals in the proportions indicated by the factors of Table 4. These factors are based on average values and merely indicate the trend which can be observed with a large number of families over considerable periods of time. Food consumption over short periods depends upon appetite and habit as well as upon activity. Muscular activity is variable from day to day, and perhaps from season to season, among both adults and children. Detailed information must be had regarding age, weight, height, build, and activity from hour to hour, if accurate estimates of the food needs of any individual are to be made.

OTHER CRITERIA FOR EVALUATING THE ADEQUACY OF DIETARIES

All of the requirements for an adequate diet can not yet be expressed quantitatively in chemical terms. The presentation of the actual quantities of various food materials used by the families studied will permit further calculations to be made as research on food values and nutritional requirements afford further quantitative data. These figures are also of interest in indicating the extent to which various commodities enter the dietary of a particular group of the population.

All organic foods are sources of energy to the body, but certain types of food materials make distinctive contributions to the diet in addition to energy. Hence, the percentage of calories derived from specified types of food is an indication of the adequacy of the diet. Refined grain products are important sources of protein as well as of energy, but are poor sources of minerals and vitamins. The biological value of their proteins is much enhanced when used in combination with milk and certain other foods. Milk is particularly important for its proteins of excellent quality, for calcium, for vitamin A, and for the pellagra-preventing factor, and in all of these respects effectively supplements the cereal products. Vegetables and fruits, while

varying widely in their energy values, are important carriers of minerals and vitamins. Citrus fruits, tomatoes, and vegetables of green and yellow color are particularly important for their vitamin C and vitamin A content. Green-colored vegetables are also valuable for iron. Most fats and sweets furnish energy only. Eggs, lean meat, and fish are sources of proteins of excellent quality, the pellagra-preventing factor, and in the case of eggs and liver, of iron and vitamin A. Family dietaries furnishing enough energy for the group nourished by them are usually found to be also otherwise adequate for good nutrition if the percentage of calories derived from these various types of food fall within the range indicated in Table 5. However, the selection of food materials within the types must be so made as to safeguard the supply of vitamins A and C, and iron.

TABLE 5.—*Percentage of calories derived from specified types of food in adequate family dietaries of low, moderate, and high cost (17)*

Type of food	Money value level		
	Low cost	Moderate cost	High cost
Bread, flour, cereals	30–40	25–30	20
Milk and cheese	20–25	25	20–25
Vegetables and fruits	12–15	15–20	18–24
Fats and oils	10–12	10–20	15–20
Sugars	10–12	10–12	10–12
Lean meat, fish, eggs	5–10	8–15	10–15

METHOD OF CALCULATING THE MONEY VALUE OF THE FOOD USED

Not all the food used by the families cooperating in this study was purchased; part of it was produced on the farm. Therefore, this report presents the money value of food rather than the cost. In general, the calculations of money value have been made on the basis of local retail prices. Table 17 gives the range of prices reported by the cooperating families for purchased commodities and the price reported most frequently. Retail prices as reported by some one or more of the cooperating families have been assigned to most home-grown products. For a few items used by some families but not purchased by any family, estimated prices of inexpensive forms, varieties, or grades were used. The money value of the food materials listed in Tables 6 and 18 have been calculated on the basis of the prices described.

FOOD SUPPLY OF UNAIDED FAMILIES

The supplies of food used by individual unaided families have been classified into two groups: (1) Those which were apparently pellagra preventing as shown by the freedom of the families from symptoms of pellagra in the late spring, and (2) those which were not pellagra preventing as evidenced by the fact that one or more members of each family succumbed to pellagra in the late spring. Two individuals in families whose food supply was classified as pellagra preventing did incur pellagra in the late spring, but in each case the individual reported a refusal to use milk, the food which

was the main source of the pellagra-preventing factor in the family dietary.

Each type of food supply has been analyzed in terms of the kinds and amounts of food materials composing it, and has been evaluated in terms of chemical composition. The results are summarized in Tables 6, 7, 9, and 10, and presented in detail in Tables 15 and 16.

COMPLETE DIETARY RECORDS OVER SHORT PERIODS

QUANTITIES OF FOOD MATERIALS USED

Satisfactory dietary records for 1 or 2 week periods in November, April, or early May, were obtained from each of the 29 unaided families, 15 supplying records for both seasons. It is significant that the families whose food supply was pellagra preventing were using not only more food, but much more milk, lean meat, fish, and eggs and somewhat more vegetables and fruit than were the families in which one or more members succumbed to the disease in the late spring. (Table 6.) The articles of food mentioned are of chief practical importance in pellagra prevention, and the extent of their use undoubtedly accounts for the difference between the two groups of families in their resistance to pellagra, and for the difference in the susceptibility of the second group at different seasons. However, since the body can store some of the surplus of pellagra-preventing factors from times of dietary plenty for use in times of dietary deficiency, the nature of the food used over a short period can not always be correlated with presence or absence of symptoms of pellagra. During the period of observation both groups were using much larger quantities of foods derived from the grain products, and of fats and oils, than is suggested by this bureau even for low-cost adequate diets (*21*), or than is estimated by the United States Department of Commerce (*15*) to be the per capita consumption for the United States, but neither group was using as much of milk, vegetables, fruit, lean meat, fish, or eggs.

TABLE 6.—*Food supply of unaided families: Average quantity and money value of food materials used per adult energy unit per day by two groups at each of two seasons, compared with a low-cost adequate dietary (21) and with food apparently utilized in the United States (15)*

Classification	Families cooperating	Average size of family	Bread, flour, and cereals	Milk and cheese	Vegetables and fruit	Fats and oils	Sugars	Lean meat, fish, and eggs	Money value
November data for families whose food supply was—		*Adult energy units*							
Pellagra preventing throughout the year	*Number* 6	4.7	*Pounds* 1.03	*Pounds* 1.02	*Pounds* 1.20	*Pound* 0.25	*Pound* 0.30	*Pound* 0.23	*Cents* 25
Not pellagra preventing throughout the year	12	5.0	1.15	.00	.93	.28	.14	.10	15
April or May data for families whose food supply was—									
Pellagra preventing throughout the year	13	4.7	1.14	1.29	.49	.29	.19	.23	22
Not pellagra preventing throughout the year	13	5.7	1.07	.03	.47	.27	.10	.09	12
Suggested low-cost adequate dietary (pellagra preventing) (*21*)	------	5.5	.68	1.70	1.28	.10	.23	.29	29
Apparent utilization of food in the United States (*15*)	------	------	.58	1.38	1.57	.14	.31	.54	------

NUTRITIVE VALUE OF THE FOOD USED

ENERGY

The food supply used over the two brief periods in November and in April or May, by families successful in warding off pellagra, furnished at each season more energy (calories) and more of each nutrient for which calculations were made, than did the food supply used by the families which incurred pellagra in the late spring. The food used in the fall by each group was more abundant than that used in the spring, as shown in Table 7. On the average, the families seemed to have food furnishing sufficient calories. Individual families varied considerably from the average, however, and, as shown in Tables 8 and 16, a number of the families whose food supply was not pellagra preventing throughout the year seemed to be underfed as well as misfed.

TABLE 7.—*Food supply of unaided families: Average nutritive value of food supply used per adult unit per day by two groups at each of two seasons, and of a suggested low-cost adequate dietary (21)*

Classification	Families	Energy	Protein	Calcium	Phosphorus	Iron	Vitamin A	Vitamin C	Pellagra-preventing factor
November data for families whose food supply was—									
Pellagra preventing throughout the year	*Number* 6	*Calories* 4,855	*Grams* 100	*Grams* 1.19	*Grams* 2.90	*Gram* 0.0160	*Units* 5,200	*Units* 160	*Units* 2.2
Not pellagra preventing throughout the year	12	3,541	62	.76	1.99	.0093	3,600	100	1.1
April or May data for families whose food supply was—									
Pellagra preventing throughout the year	13	3,900	75	1.13	2.31	.0127	4,100	99	1.6
Not pellagra preventing throughout the year	13	3,035	51	.77	1.93	.0086	700	95	0.6
Suggested low-cost adequate diet (pellagra preventing) (*21*)	-------	3,000	70	.75	1.41	.0162	5,300	170	1.5

TABLE 8.—*Food supply of unaided families: Number of families in each of two groups using food which furnished specified number of calories per adult energy unit per day at each of two seasons*

Classification	Families cooperating	Families whose food supply furnished per adult energy unit per day—						
		Under 2,100 calories	2,100–2,699 calories	2,700–3,299 calories	3,300–3,899 calories	3,900–4,499 calories	4,500–5,099 calories	5,100 calories and over
November data for families whose food supply was—								
Pellagra preventing throughout the year	*Number* 6	*Number* -------	*Number* -------	*Number* -------	*Number* -------	*Number* 2	*Number* 3	*Number* 1
Not pellagra preventing throughout the year	12	3	3	1	4	-------	1	-------
April or May data for families whose food supply was—								
Pellagra preventing throughout the year	13	-------	-------	3	5	1	3	1
Not pellagra preventing throughout the year	13	2	3	3	4	1	-------	-------

PROTEIN

At both seasons the families in each of which some cases of pellagra developed in the late spring used food which furnished, on the average, less than 68 grams of protein per adult unit per day. This is less than is usually considered a safe allowance over the average minimum requirement. Much of it was derived from grain products whose proteins are of lower biological value than those from milk, eggs, or lean meat.

MINERALS

The estimated amounts of calcium and phosphorus in the food of both groups were larger than would be expected from a consideration of the items of food used, because the flour generally used was a self-rising variety containing added calcium phosphate. All but two of the families who had pellagra-preventing food all the year had more than 0.68 gram of calcium per adult unit, and 1.32 grams of phosphorus in their food. Even with the extra calcium in the flour, the food supply furnished less calcium than is considered a satisfactory allowance in the case of 6 of the 13 unaided families among whom cases of pellagra occurred in the late spring. Indeed, in the case of four families the estimated amount was less than 0.45 gram, the average minimum quantity required for maintaining calcium equilibrium in the adult man. Only for 3 of 13 families whose food was pellagra preventing throughout the year, and only for 1 of 13 families in each of which some members succumbed to the disease in the late spring, did the food used in April or early May furnish an ample allowance of iron, i. e., 0.0150 gram or more per adult unit. (Table 16.)

VITAMINS

In the fall the food of each group of families furnished enough of the pellagra-preventing factors to keep the members free from the disease. In the spring the food of those incurring pellagra included very meager amounts. Each group used green vegetables more liberally in the fall than in the spring. This increased the vitamin A value of their diets at that season. The use of whole milk at both seasons by the families which were not subject to pellagra, further enriched their diets in vitamin A. The fall diets of each group furnished more vitamin C than did the spring diets, but for all families, and at both seasons, the quantities were probably less than is desirable. (Table 7.)

It is interesting to consider whether the more liberal intake of protein, minerals, and vitamins on the part of families successful in warding off pellagra was due merely to the use of larger quantities of all food materials or to the use of food of a different character. That the latter is the case is shown by Tables 9 and 10. Table 9 shows the quantities of the various nutrients per 3,000 calories of the food as reported by each group of families in November, and in April or May. On this basis the differences in the food supply of the two groups appear less pronounced, but are still large enough to justify the statement that the food of the two groups was decidedly different in character. Table 10 shows that the chief difference in the two types of food supply lay in the extent to which milk and cheese were used. Compared with the adequate low-cost dietary suggested by this

bureau (*21*) the food supply of both groups at both seasons was lower than is desirable in milk, in vegetables and fruits, and in lean meat, fish, and eggs, and correspondingly higher than seems desirable in foods derived from the cereal grains and in fats and oils.

TABLE 9.—*Food supply of unaided families: Nutritive value per 3,000 calories of the food used by two groups of unaided families at each of two seasons, compared with a low-cost adequate dietary (21)*

Classification	Families cooperating	Protein	Calcium	Phosphorus	Iron	Vitamin A	Vitamin C	Pellagra-preventing factor
November data for families whose food supply was—								
Pellagra preventing throughout the year	*Number* 6	*Grams* 62	*Gram* 0.74	*Grams* 1.79	*Gram* 0.0099	*Units* 3,200	*Units* .00	*Units* 1.4
Not pellagra preventing throughout the year	12	52	.64	1.68	.0079	3,050	85	.9
April or May data for families whose food supply was—								
Pellagra preventing throughout the year	13	58	.87	1.78	.0098	3,150	75	1.2
Not pellagra preventing throughout the year	13	50	.76	1.91	.0085	700	95	.6
Suggested low-cost adequate diet (pellagra preventing) (*21*)	----	70	.75	1.41	.0162	5,300	170	1.5

TABLE 10.—*Food supply of unaided families: Percentage of calories derived from specified types of food materials, as used by two groups at each of two seasons, compared with a low-cost adequate dietary (21) and with food apparently utilized in the United States (15)*

Classification	Families cooperating	Average energy value per adult unit	Calories derived from—					
			Bread, flour, and cereals	Milk and cheese	Vegetables and fruit	Fats and oils	Sugars	Lean meat, fish, and eggs
November data for families whose food supply was—								
Pellagra preventing throughout the year	*Number* 6	*Calories* 4,855	*Per cent* 49	*Per cent* 7	*Per cent* 8	*Per cent* 25	*Per cent* 9	*Per cent* 2
Not pellagra preventing throughout the year	12	3,541	50	1	9	30	7	3
April or May data for families whose food supply was—								
Pellagra preventing throughout the year	13	3,900	45	11	3	28	8	5
Not pellagra preventing throughout the year	13	3,035	54	1	3	34	6	2
Suggested low-cost adequate dietary (pellagra preventing) (*21*)	----	3,000	36	18	13	13	12	8
Food apparently utilized in the United States (*15*)	----	[1] 3,650	27	14	13	14	15	17

[1] Per capita.

USE OF SPECIFIED FOOD MATERIALS IN RELATION TO THE INCIDENCE OF PELLAGRA

How long a person can live on an inadequate diet without incurring pellagra depends both upon the degree of the inadequacy of the diet and upon the bodily store of the pellagra-preventing factor which the person has acquired during times of a dietary surplus.

During a 2 to 6 month period previous to the last physical examinations made of the cooperating families (the last 10 days of May or

after the middle of June), each family kept a record of the quantities of milk, lean meat, fish, eggs, fruits, and vegetables used.

It was found that the 14 unaided families whose food supply was pellagra preventing throughout the year used, on the average, 2¼ cups of milk per person per day, about 3 ounces of fruit and succulent vegetables, and about 3 ounces of lean meat. (Table 11.) From these families, 7 men, 14 women, and 42 children were periodically examined for pellagra. Only two persons were suffering from the disease in the late spring, an adult woman who would not drink milk and a 10-year-old girl who was reported as having a very poor and "finicky" appetite. The family dietaries were undoubtedly pellagra preventive, and these two persons were the victims of their own faulty food habits. No further cases of pellagra developed later in the summer in any of these families.

TABLE 11.—*Food supply in relation to pellagra incidence among unaided families: Average reported use of pellagra-preventing food materials in the late winter and spring, history of pellagra among individuals periodically examined, and pellagra incidence in the late spring*

Classification	Families cooperating	Reported use per capita per day of—			Period covered by report on food	Individuals given periodic physical examinations		
		Milk	Vegetables and fruit	Lean meat, fish, and eggs		Total	With history of pellagra	In whom pellagra was observed in late spring
Families whose food supply was—								
Pellagra preventing throughout the year	*Number* 14	*Cups* 2.26	*Pound* 0.22	*Pound* 0.16	*Weeks* 4–16	*Number* 63	*Number* 11	*Number* [1] 2
Not pellagra preventing throughout the year	15	[2] .18	.15	.13	4–18	81	22	31

[1] These individuals refused to drink milk.
[2] Averages based on data from 13 families.

Over parallel periods in the late winter and early spring the 15 unaided families in each of which one or more persons incurred pellagra in the late spring used, on the average, less than one-fifth cup of milk, less than 3 ounces of vegetables and fruit, and less than 3 ounces of lean meat, fish, and eggs per person per day. From these families 11 men, 21 women, and 49 children were examined; of these, 4 men, 12 women, and 6 children reported a history of pellagra. Before the end of the summer 1 or more members of each family, altogether 4 men, 13 women, and 14 children, had incurred pellagra.

Even on these very restricted diets not every member in each family succumbed to pellagra. The normal seasonal changes in diet may cut short some cases before they reach a diagnosable stage. Probably the different members of a family group seldom eat the same proportions of the food available at any one time. When there is a shortage of certain food materials some members may be favored with a larger share of the scarce and, therefore, the choice foods; when all kinds of food are plentiful, individual food preferences will determine choice. Apparently some members of each family group are more successful in fortifying themselves against a future shortage of pellagra-preventing foods than are others.

It is of interest to compare the diets of these unaided families and of the subjects of Goldberger's experiment in the fall of 1915, when pellagra was first experimentally induced in man by dietary means (*7*). In consideration of pardon, 11 convicts in a State penitentiary volunteered to subsist for six months on a 1-sided diet consisting of highly milled wheat flour, bolted maize meal, grits, cornstarch, white rice, cane sugar, homemade cane sirup, sweetpotatoes, pork fat, cabbage, collards, turnip greens, and coffee. During the first three months some buttermilk was used in making the wheat biscuits. The average energy intake of the volunteers was from 2,500 to 3,500 calories, including 41 to 54 grams of protein, 80 to 90 per cent of which was from cereal sources. About 51 per cent of the calories were derived from grain products, 6 per cent from vegetables, 12 per cent from sugar and sirup, and 31 per cent from fat. This diet was, therefore, not only practically devoid of the pellagra-preventing factor, but was low in mineral elements and vitamins A, B, and C, as well as deficient in certain amino acids.

Only men of good health and with no previous history of pellagra were accepted as volunteers. But during the second month after beginning to use this restricted ration, they all began to suffer from weakness, abdominal pain or discomfort, and headache, and before the six months were over, 6 of the 11 men had developed a well-marked eruption of the skin, the earliest beginning about the end of the fifth month of the diet. All of the subjects lost weight, particularly during the last month, and even those who did not incur skin lesions developed the symptoms frequently encountered in pellagrous communities, i. e., loss in weight, exhaustion, dizziness, nervousness, headache, insomnia, burning and redness of the tongue, and cramps. Hence their condition was diagnosed as "pellagra sine pellagra", i. e., not definitely diagnosed as having pellagra, but were classed as suspects, who, it was felt, would have developed the confirmatory skin lesions had the test been permitted to run longer.

The chief difference between the diets of these subjects in Goldberger's experiment and the diets used in April or early May by the farm families among whom pellagra was prevalent in late spring lies in the amounts of lean meat and milk used by the farm families. The volunteering convicts received practically no milk and no lean meat; whereas, on the average, the unaided families among whom pellagra occurred used about one-fifth cup of milk and from 2 to 3 ounces of lean meat, fish, or eggs per person per day. On this small per capita allowance of pellagra-preventing foods some members in each family kept free from outward manifestation of the disease while others succumbed.

In general, the results on the relation of the food supply to pellagra incidence among these farm families are in harmony with the findings secured in a study conducted by Goldberger and his colleagues (*14*) covering a village population of about 23,000 mill operatives in South Carolina over a period of five years.

FOOD SELECTION IN RELATION TO MONEY VALUE OF DIETS

A shortage of home-produced foods and of ready cash makes evident the nature of the competition between foods that satisfy the appetite and foods that are also otherwise necessary for an adequate

diet. Some families in which one or more members were suffering from pellagra in the late spring had a scanty food supply in the early spring, as judged from records of their total consumption for a week in April or early May. In three of the families in which children as well as adults suffered from pellagra (families Nos. 16, 28, and 29) there seemed to be a real food shortage, as shown in Table 16 of the appendix. The food furnished 1,833, 1,974, and 2,953 calories per adult energy unit per day, respectively, as compared with a standard of 3,000 calories; 0.46, 0.42, and 0.99 gram of calcium as compared with a standard of 0.68 gram per adult unit; 1.06, 1.20, and 2.73 grams of phosphorus as compared with a standard of 1.32 grams; 0.0042, 0.0034, and 0.0078 gram of iron as compared with a standard of 0.0150 gram; and 0.4, 0.1, and 0.5 unit of pellagra-preventing food material as compared with a standard of 1 unit. The relatively high figures for calcium and phosphorus in the case of family No. 29 are due not to the use of milk, which is usually the most important natural food source of these elements, but to the calcium phosphate in the self-rising flour. No milk or cheese was used by any of these three families; only family No. 29, which used some fish and beef, had foods furnishing proteins from animal sources. Family No. 16 used some cabbage, peas, and other vegetables; family No. 28 used no vegetables; and family No. 29, a few sweetpotatoes, tomatoes, and legumes. In these three families from 91 to 97 per cent of the calories were derived from white flour, corn meal, rice, granulated sugar, and lard.

The foods used by these three families consisted of the cheapest food sources of energy, and had a calculated money value of 9, 7, and 13 cents, respectively, per adult energy unit per day. Adequate diets could not have been secured for this money allowance even with wiser spending.

In still another family (No. 21) in which children and adults were suffering from pellagra at the last physical examination in the late spring, the food used in May furnished 4,794 calories per adult energy unit per day. Ninety-seven per cent of the calories were derived from grain products, fats, and sugar, for a money value of about one-third cent per 100 calories. Calculated on the same price basis, a low-cost adequate diet (*21*) has a value of approximately 1 cent per 100 calories. Obviously this family could not have secured a fully balanced diet for the same money even by reducing the total calories by one-third or one-half. A marked improvement in the quality of the diet could have been made, however, had the family used smaller quantities of the staple foods and included some milk and lean meat, and more vegetables in its diet.

The food of the unaided families among whom pellagra did not occur in the late spring furnished, on the average, 3,900 calories per adult energy unit per day, at a (calculated) money value of 0.56 cent per 100 calories. It was pellagra preventing but would have been better balanced in other respects had it included more vegetables, milk, eggs, and lean meat. Without increasing the money value assigned to food, these families could not have secured the complete low-cost diet suggested by this department (*21*), but they would have had money for a larger proportion of the protective foods had they been willing to eat somewhat less and reduce their total food intake to the standard of 3,000 calories per adult energy unit per day.

128705°—32——3

From observations made by Benedict and his coworkers (*2*), it would appear that in case of serious food shortage, a considerable reduction in diet can be safely undertaken by adults over a period of several months, provided the diet is well balanced. The body seems to adjust itself quite satisfactorily to a lower plane of nutrition. It is not known, however, what effects, if any, more serious than the temporary stunting of growth would occur in children.

USE OF SUPPLEMENTARY FOODS IN RELATION TO INCIDENCE OF PELLAGRA AMONG AIDED FAMILIES

In Lee County there were many families whose food resources and whose economic condition indicated that they would probably succumb to pellagra in the late spring if not given aid during the winter and spring. To 44 of these families certain pellagra-preventing food materials were furnished in definite quantities for known periods previous to the final physical examinations in the late spring. Table 20 gives detailed information on the supply of protective foods in relation to the incidence of pellagra in each of these families, and Table 12 gives the summary for each group receiving definite quantities of each food.

TABLE 12.—*Food supply in relation to pellagra incidence among aided families: Quantity of pellagra-preventing food material furnished per capita per day for specified periods previous to physical examination in late spring, history of pellagra among individuals periodically examined, and pellagra incidence in late spring*

Supplementary food furnished			Individuals given periodic physical examinations		
Kind	Quantity furnished per capita per day	Period previous to last examination	Total	With history of pellagra	In whom pellagra was observed in late spring
		Weeks	*Number*	*Number*	*Number*
Dry skim milk	2 ounces	8–18	54	35	6
Do	4 ounces	8	9	3	0
Evaporated milk	1 pound	8–24	71	38	7
Wheat germ	1 ounce	16–18	24	8	2
Do	2 ounces	8	16	5	2
Cured lean pork	8 ounces	8–20	15	12	4
Canned tomatoes	1½ pints	8	13	1	0
Pure dry yeast	1 ounce	8	13	3	0

DRY SKIM MILK

From a group of 10 families receiving 2 ounces of dry skim milk per person per day for 8 to 18 weeks, 54 persons, including 1 man, 16 women, 18 boys, and 19 girls, were periodically examined for pellagra. Of these, the man, 15 women, and 19 children had suffered from pellagra previously. By May and June, after receiving milk for 16 weeks or more, 1 girl and 5 women showed symptoms of the disease. The child, who was then suffering from a mild attack, reported no history of pellagra. The women had all suffered from pellagra before but reported that their cases this year were less severe than formerly.

From three families receiving 4 ounces of dry skim milk per person per day for 8 weeks, 9 persons, including 1 man, 4 women, 3 boys, and 1 girl, were under observation. Three of the women reported a his-

tory of pellagra. None of the persons observed showed symptoms of the disease when the final examinations were made.

EVAPORATED MILK

From 14 families receiving a pound of evaporated milk per person per day for 8 to 24 weeks, 71 individuals were regularly examined. These included 8 men, 16 women, 25 boys, and 22 girls. Six of the men, 13 women, and 19 children had previously suffered from pellagra; 2 men and 4 women, although they had been furnished the milk for 16 weeks or more, had the disease in the late spring, but in milder form than before. One child was suffering from pellagra when the supplementary feeding was begun. His condition was improved, but not cured, by the use of 1 pound of the milk daily for 8 weeks; 4 other persons, however, were cured after receiving the milk for this period.

WHEAT GERM

In a group of 4 families receiving an ounce of wheat germ per person per day for approximately 4 months, 24 individuals, including 3 men, 4 women, 10 boys, and 7 girls were under observation. One man, 2 women, and 5 children reported a history of pellagra. By the end of the period one man and one woman showed symptoms of the disease. The man reported a negative pellagra history but was suffering with a mild case when last examined. The woman had suffered from the disease before.

From 3 families receiving 2 ounces of wheat germ per person per day for 8 weeks, 16 individuals, including 1 man, 6 women, 3 boys, and 6 girls were examined periodically. The man and three women were suffering from pellagra in April when the supplementary feeding was begun. By the middle of June, symptoms of sore mouth and burning skin still persisted in two of the women; the others were apparently free from the disease.

CURED LEAN PORK

From 3 families receiving one-half pound cured lean pork per person per day for approximately 5 months, 7 persons were examined at regular intervals, including 1 man, 4 women, and 2 children. All but one woman had reported a history of pellagra. When the last physical examinations were given the last week in May, three weeks after the supply of meat had been exhausted, three women were suffering from pellagra. In 3 other families 2 men, 3 women, and 3 children were examined in April for the first time. All but one man were found to be suffering from pellagra. These families were given cured lean pork, one-half pound per person per day. After eight weeks, the interval between the first and last examinations, the symptoms of pellagra had completely disappeared from all but one woman, and her condition was improved.

CANNED TOMATOES

Two families in which there were 2 men, 3 women, and 8 children were given 1½ pints of canned tomatoes per person per day for 8 weeks. One person in one family was suffering from pellagra when the supplementary feeding was begun; otherwise both families reported a

negative pellagra history. Two months later when the pellagrin was again examined, he was free from all symptoms of the disease. The second family owned a cow, and used about 2 quarts of milk daily. This increased, of course, the pellagra-preventing value of their diet. No symptoms of pellagra were observed in either family at the last physical examination in June.

PURE DRIED YEAST

In 2 families in which 2 men, 1 woman, and 10 children were examined in April, 1 boy and 2 girls were suffering from pellagra. One ounce of pure dried yeast was furnished each individual daily for the next two months. No symptoms of the disease were observed in any members of either household at the end of that period.

GENERAL OBSERVATIONS

In some cases the quantities of supplementary foods furnished per person per day in this investigation were smaller than have been reported by the Public Health Service (*5*, *6*, *8*, *9*, *10*, *11*, *23*) to be pellagra preventing when used in addition to a constant basal ration very deficient in pellagra-preventing factors. The food supply that the aided families furnished for themselves was probably not pellagra preventing, as it was very similar to that used in the early spring by the unaided families in each of which one or more members succumbed to pellagra late in the same spring. Probably it contained as much of the protective factor as the experimental basal ration used by the Public Health Service, and possibly more. However, only one family (No. 72) reported the continued and liberal use of a markedly protective food other than that furnished. There is every reason to believe that the furnished foods provided the major share of the pellagra-preventing food used by the aided families and that the lessened incidence, or the moderation in the severity of the cases which did occur, can be attributed chiefly to the supplementary foods in the quantities given.

From the data on health history and food resources given in Tables 15 and 19 it seems likely that had the families which were supplied with pellagra-preventing food continued without aid, the incidence of pellagra among them would have been as high during the period of observation as it had been in their past, or as high as in the current year among those unaided families whose food supply was not pellagra preventing. The use of the supplementary foods unquestionably reduced the incidence of the disease in the aided families.

That no group of families receiving supplementary food was entirely free from the disease may be due to the fact that the quantities furnished were insufficient for the needs of a given individual, or it may be due to the failure of the individuals incurring the disease to use their full share of the furnished food. While it is not suggested that the quantities of supplementary food furnished in this demonstration provided the most suitable per capita allowance, it is clear that when used to supplement a family diet, these food materials are efficacious in greatly reducing the incidence of the disease.

INCIDENCE OF PELLAGRA IN RELATION TO SEX AND AGE

The incidence of pellagra among the cooperating families both in the past and during the year of the study appeared to be higher among the adult women than among the men and children. This is shown in Table 13. Inasmuch as the supplementary pellagra-preventing food was furnished to aided families in definite quantities per person, and as the families made an effort to distribute it equally among their members, the relatively high incidence of pellagra among adult women (usually mothers of families) indicates that they may need more of the pellagra-preventing factor than do men and children, or habitually eat relatively less, especially in case of restricted quantities.

TABLE 13.—*Incidence of pellagra in relation to sex and age: Average for all cooperating families*

Classification	Individuals examined periodically	Individuals with history of pellagra		Individuals discovered with pellagra at last examination	
	Number	*Number*	*Per cent*	*Number*	*Per cent*
Unaided families whose food supply was:					
Pellagra preventing throughout the year—					
Male, 18 years and over	7	4	57	0	0
Female, 18 years and over	14	4	29	[1] 1	[1] 7
Male, under 18 years	20	2	10	0	0
Female, under 18 years	22	1	5	[1] 1	[1] 5
Not pellagra preventing throughout the year—					
Male, 18 years and over	11	4	36	4	36
Female, 18 years and over	21	12	57	13	62
Male, under 18 years	29	3	10	9	31
Female, under 18 years	20	3	15	5	25
All aided families whose food supply was supplemented by pellagra-preventing foods:					
Male, 18 years and over	21	12	57	3	14
Female, 18 years and over	57	42	74	16	28
Male, under 18 years	71	24	34	1	1
Female, under 18 years	66	27	41	1	1

[1] Would not drink milk.

SUGGESTIONS FOR IMPROVING DIETS

The prevalence of pellagra among the unaided families during this investigation appeared to be related to their supply of home-produced food. Of the 14 unaided families among whom pellagra was not observed, 8 families owned cows, raised hogs for food, and had vegetable gardens; only 1 unaided family reporting an equal provision for its food supply incurred pellagra while under observation. Milk appears to be a food of prime importance in the diet of these farm families. It can easily be used in the quantities necessary for pellagra prevention, and is of great value in reinforcing the diet in many other respects. Other foods furnished by the farm for home use are also of value in pellagra prevention, and should be included in the diet, but in addition to, not as a substitute for, milk.

Of the 59 other families included in this study only one-fourth had cows; about one-half had swine; three-fourths had poultry; and about one-half had gardens. About two-thirds of them were tenant farmers on small farms. The number of persons in each household was large, averaging six to seven persons. It may be of interest to compare these figures with statistics for Lee County as a whole. According to the

United States Census of Agriculture for 1925, (*22*), 78 per cent of the farmers were tenants and 80 per cent of all the farms were less than 50 acres in size. The average value per acre for land and buildings was $64.55, and the average value of crops raised in 1924 was approximately $31 per acre. The average value of the livestock, including approximately three swine per farm, was about $250. One cow was milked for every two or three farms. The poultry and eggs produced in 1924 had a value of approximately $30 per farm. Such facts show that the cash incomes and the food resources for farm families in Lee County as a whole are very low, and the families face a very difficult problem in the matter of securing an adequate diet.

Extension workers have amply demonstrated that the acre used for the home garden can be the most profitable acre on the farm. It is also well known that the milk cow and swine provide foods from animal sources most economically. Public-health agencies (*4*) have pointed out that most rural families must keep well-managed and productive vegetable gardens, poultry flocks, milk cows, and pigs, if they are to have the food materials needed for normal nutrition not only readily available, but available at a relatively low cost. A program for the home production and conservation of food should be undertaken which will make available for every week in the year at least the minimum quantities of protective foods. These quantities are summarized in Table 18 for a family of 7 with 2 adults and 5 children, the average family size among the cooperating families. For families of this size a food supply including these food materials would have a money value of $575 to $600 per year if calculated at the retail prices current in Lee County when this study was made (1929–30). The families cooperating in this study could afford such diets only if they produced a large share of the food on their own farms. This has been found expedient by most successful farm families.

SUMMARY AND CONCLUSIONS

The food supply of 73 farm families of Lee County, S. C., has been studied in its relation to the incidence of pellagra. In April or early May the diets of the families in which one or more members showed symptoms of the disease in the late spring were found to consist largely of breadstuffs, sweets, and fats. These foods may be satisfying to the palate and furnish energy very cheaply, but they are inadequate in protein, minerals, and vitamins. In many cases the amounts of calcium and iron were lower than dietary standards for good nutrition recommend, and the diets were poor in vitamins A and C as well as grossly deficient in the pellagra-preventing factor. The families successful in warding off pellagra used diets more abundant in every respect, and containing a much higher proportion of milk than those used by families in each of which one or more members incurred pellagra in the late spring.

The investigators supplied definite quantities of one of six pellagra-preventing food materials to 44 families whose health history and economic resources indicated that without aid they would be unsuccessful in warding off pellagra in the late spring. The articles of food furnished were dry skim milk, evaporated milk, cured lean pork, wheat germ, canned tomatoes, and pure dry yeast. Periodic examinations for pellagra revealed that the incidence and severity of the

disease among these aided families was less than they had experienced in former years and much less than unaided families of similar resources experienced during the period under observation.

Exact knowledge of the food intake of each individual for the entire period of the investigation could not be secured with the supervision available. Hence it can not be affirmed that the supplementary food materials in the quantities used were the sole source of the pellagra-preventing factor; nor is any claim made that the food even of those who did not incur pellagra contained all the pellagra-preventive factor desirable for an individual. However this study does afford a practical demonstration that the addition of 2 to 4 ounces of dry skim milk or 1 pound of evaporated milk, or 1 to 2 ounces of wheat germ, or 1½ pints of canned tomatoes, or one-half pound of cured lean pork, or 1 ounce of pure dry yeast per person per day to the food supply customarily used in winter and early spring suffices to reduce greatly the incidence of pellagra among families which in times of stress subsist on a very monotonous and 1-sided diet containing very little milk, lean meat, fish, or eggs.

The diets of the farm families cooperating in this study would also be much improved in other respects if a larger proportion of their food consisted of dairy products, fruits, vegetables, lean meat, fish, and eggs. For most farm families the most economical means of providing these important foods is through a carefully planned program of home food production and conservation.

APPENDIX

Detailed data on food supply and pellagra incidence among 73 farm families in Lee County, S. C., are given in Tables 14 to 20.

TABLE 14.—*Family size, land tenure, and reported food resources of individual families, classified by the type of diet used throughout the year or by kind of supplementary food given*

UNAIDED FAMILIES WHOSE FOOD SUPPLY WAS PELLAGRA PREVENTING THROUGHOUT THE YEAR

Family No.	Family size by age groups			Land tenure		Report on possession of—					
	18 years and over	11 to 17 years	Under 11 years	Type	Occupancy of present farm	Cows	Hogs	Poultry flock		Vegetable garden	Dried peas or beans for winter use
								For meat	For eggs		
	Number	*Number*	*Number*		*Years*						
1	5	0	2	Hired man	1	Yes	No	No	Yes	No	No.
2	2	0	2	Owner	11	No	Yes	Yes	Yes	Yes	Yes.
3	2	1	3	do	3	Yes	Yes	Yes	Yes	Yes	Yes.
4	2	2	7	do	21	Yes	Yes	Yes	No	Yes	Yes.
5	2	0	0	do	15	No	No	No	No	No	No.
6	5	1	1	do	30	Yes	Yes	Yes	No	Yes	Yes.
7	2	1	2	do	5	Yes	Yes	Yes	Yes	Yes	Yes.
8	2	1	1	Tenant	16	Yes	Yes	Yes	Yes	Yes	Yes.
9	2	3	5	Owner	3	Yes	Yes	Yes	Yes	Yes	No.
10	2	3	3	Tenant	18	Yes	Yes	No	Yes	Yes	Yes.
11	3	3	2	do	⅓	Yes	No	No	No	Yes	(?)
12	2	3	4	do	10	Yes	Yes	No	Yes	Yes	Yes.
13	2	3	2	Owner	18	Yes	No	No	Yes	Yes	Yes.
14	2	0	3	do	3	No	Yes	No	Yes	No	No.

TABLE 14.—*Family size, land tenure, and reported food resources of individual families, classified by the type of diet used throughout the year or by kind of supplementary food given*—Continued

UNAIDED FAMILIES WHOSE FOOD SUPPLY WAS NOT PELLAGRA PREVENTING THROUGHOUT THE YEAR

Family No.	Family size by age groups			Land tenure		Report on possession of—					
	18 years and over	11 to 17 years	Under 11 years	Type	Occupancy of present farm	Cows	Hogs	Poultry flock		Vegetable garden	Dried peas or beans for winter use
								For meat	For eggs		
	Number	*Number*	*Number*		*Years*						
15	2	0	3	Owner	1	No	Yes	Yes	Yes	Yes	No.
16	2	4	2	Tenant	5	No	Yes	No	No	No	No.
17	2	0	0	do	2	No	Yes	No	Yes	Yes	Yes.
18	2	3	1	do	10	No	Yes	No	Yes	Yes	Yes.
19	2	2	2	do	5	No	No	Yes	No	Yes	Yes.
20	5	1	3	Owner	50	No	Yes	Yes	No	Yes	Yes.
21	2	0	2	Hired man	0	No	Yes	No	Yes	No	No.
22	2	0	0	Owner	6	No	No	Yes	Yes	Yes	Yes.
23	2	1	4	Hired man	10	Yes	Yes	Yes	Yes	Yes	Yes.
24	2	2	4	do		No	No	No	No	No	Yes.
25	3	3	0	Owner	13	Yes	Yes	Yes	No	Yes	Yes.
26	4	0	1	do	40	No	Yes	Yes	Yes	Yes	No.
27	5	3	2	Tenant	6	Yes	Yes	Yes	Yes	Yes	Yes.
28	2	2	5	do	3	No	No	No	No	No	No.
29	2	3	3	do	1	No	No	No	No	No	Yes.

AIDED FAMILIES WHOSE FOOD SUPPLY WAS SUPPLEMENTED WITH DRY SKIM MILK

30	2	1	5	Tenant	1	No	No	Yes	Yes	Yes	Yes.
31	5	0	0	do	¾	No	Yes	No	No	No	Yes.
32	2	0	4	Overseer	1	No	Yes	No	Yes	Yes	No.
33	3	2	2	Owner	17	No	No	Yes	No	No	No.
34	2	2	1	Tenant	1	No	No	Yes	Yes	Yes	Yes.
35	2	2	5	do	3	No	Yes	Yes	Yes	Yes	Yes.
36	2	4	5	do	3	No	Yes	Yes	Yes	Yes	Yes.
37	2	2	1	Hired man	1	No	No	No	No	No	Yes.
38	2	0	5	Cropper	½	No	No	Yes	Yes	Yes	Yes.
39	2	4	5	Tenant	3	Yes	Yes	Yes	No	No	Yes.
40	1	0	3	do	10	Yes	Yes	Yes	Yes	Yes	Yes.
41	2	0	2	(?)	(?)	No	No	Yes	No	No	Yes.
42	2	1	0	(?)	9	Yes	No	Yes	Yes	No	Yes.

AIDED FAMILIES WHOSE FOOD SUPPLY WAS SUPPLEMENTED WITH EVAPORATED MILK

43	2	0	5	Hired man	3	No	No	No	No	Yes	No.
44	3	4	4	Tenant	2	No	No	Yes	Yes	No	No.
45	2	0	0	Hired man	½	No	Yes	No	No	Yes	Yes.
46	2	3	4	Tenant	10	No	Yes	No	No	No	No.
47	2	1	2	do	½	No	No	Yes	Yes	No	No.
48	4	0	1	do	3	No	No	No	No	Yes	No.
49	4	0	1	Hired man	⅓	No	Yes	No	Yes	No	No.
50	2	0	3	Tenant	1	No	Yes	Yes	No	No	No.
51	3	3	2	do	4	No	Yes	Yes	No	Yes	Yes.
52	2	1	4	do	2	No	Yes	No	No	Yes	No.
53	1	0	1	do	¼	Yes	Yes	Yes	No	No	Yes.
54	2	1	2	(?)	¾	(?)	(?)	(?)	(?)	(?)	(?)
55	2	3	4	Tenant	8	No	Yes	No	Yes	No	No.
56	2	1	4	do	4	No	Yes	Yes	Yes	No	Yes.

AIDED FAMILIES WHOSE FOOD SUPPLY WAS SUPPLEMENTED WITH WHEAT GERM

57	3	3	2	Tenant	2	No	Yes	Yes	No	Yes	No.
58	2	2	1	Owner	9	Yes	No	Yes	Yes	Yes	No.
59	2	3	5	do	24	No	Yes	Yes	No	Yes	Yes.
60	3	2	2	Tenant	¾	No	No	Yes	Yes	Yes	Yes.
61	3	1	3	do	⅓	Yes	No	No	No	No	No.
62	2	3	5	Owner	6	(?)	Yes	Yes	Yes	No	Yes.
63	3	0	1	Tenant	⅓	No	No	No	(?)	No	No.

TABLE 14.—*Family size, land tenure, and reported food resources of individual families, classified by the type of diet used throughout the year or by kind of supplementary food given*—Continued

AIDED FAMILIES WHOSE FOOD SUPPLY WAS SUPPLEMENTED WITH LEAN CURED PORK

Family No.	Family size by age groups			Land tenure		Report on possession of—					
	18 years and over	11 to 17 years	Under 11 years	Type	Occupancy of present farm	Cows	Hogs	Poultry flock		Vegetable garden	Dried peas or beans for winter use
								For meat	For eggs		
	Number	*Number*	*Number*		*Years*						
64	2	1	1	Tenant	4	No	No	Yes	Yes	Yes	No.
65	1	1	1	do	1	No	No	Yes	Yes	Yes	No.
66	3	0	0	Hired man	3	Yes	No	Yes	Yes	Yes	No.
67	2	1	1	Tenant	3	Yes	No	No	Yes	No	No.
68	2	1	1	Hired man	¼	No	No	No	No	No	No.
69	2	0	0	do	2	Yes	No	No	Yes	No	No.
AIDED FAMILIES WHOSE FOOD SUPPLY WAS SUPPLEMENTED WITH CANNED TOMATOES											
70	2	0	4	Tenant	3	No	Yes	No	Yes	No	Yes.
71	3	2	3	do	⅓	Yes	Yes	No	Yes	No	Yes.
AIDED FAMILIES WHOSE FOOD SUPPLY WAS SUPPLEMENTED WITH PURE DRY YEAST											
72	2	4	2	Tenant	3	No	Yes	Yes	Yes	Yes	No.
73	3	2	3	do	3	No	Yes	No	No	No	No.

TABLE 15.—*Food supply of unaided families: Quantity, in pounds, of food materials used per adult energy unit at each of two seasons by individual families with two types of diets*

NOVEMBER DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS PELLAGRA PREVENTING THROUGHOUT THE YEAR

Family No.	Family size in adult energy units	Grain products					Milk and cheese		Vegetables and fruit										Fats and oils			Sugars			Lean meat, fish, and eggs					
		Flour	Corn meal	Grits	Rice	Bread and other cereal	Milk	Cheese	Potatoes	Sweet potatoes	Cabbage	Collards	Other greens	Peas	Tomatoes	Other vegetables	Legumes	Berries	Other fruit	Salt pork and bacon	Lard	Butter	Sugar	Molasses and sirup	Preserves and jelly	Poultry	Fresh pork and other meat	Ham	Beef	Fish	Eggs
1	5.0	0.34	0.44	0.24	0.20	----	0.09	0.03	----	2.16	----	----	----	0.38	0.14	----	----	----	----	0.11	0.17	----	0.28	0.34	----	0.17	----	0.08	----	0.25	----
2	3.2	1.38	.27	.13	.12	----	----	----	----	.72	----	0.17	----	.52	.10	0.12	----	----	----	.09	----	----	.26	.19	0.06	.09	----	----	0.13	----	0.01
3	4.8	.60	.61	.06	----	----	2.62	----	----	----	----	.27	0.06	.06	.02	.12	0.01	----	----	.15	.09	----	.06	.15	.06	----	----	----	----	----	.00
4	7.7	.56	.46	.30	.13	----	3.43	----	----	1.17	----	.09	----	.08	----	.16	----	0.05	----	.17	.07	----	.18	.11	----	----	----	----	----	----	----
5	2.2	.39	2.13	----	----	----	----	----	----	.13	----	----	----	.22	----	----	.03	----	----	.18	----	----	----	----	----	.45	----	----	----	.26	----
6	5.4	.63	.58	----	.10	----	----	----	----	.36	----	----	----	.11	----	.11	.13	----	----	.24	.21	----	.10	----	----	----	----	----	----	----	----

APRIL OR MAY DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS PELLAGRA PREVENTING THROUGHOUT THE YEAR

2	3.2	0.56	0.28	----	----	----	0.33	----	----	0.47	----	----	0.07	0.04	0.04	0.07	----	----	0.15	0.31	----	----	0.22	0.11	----	----	----	----	----	0.27	0.08
3	4.8	.15	.46	.07	.02	0.04	2.81	----	0.02	.24	0.14	----	.06	----	----	.03	0.02	0.16	----	.03	0.12	----	.08	.04	----	0.04	----	0.15	----	.11	.04
4	7.7	.65	.35	----	.03	----	1.71	----	.31	----	.08	----	.11	.08	.03	.13	----	----	----	.17	.09	----	.08	.22	----	.03	----	----	----	.22	.06
5	2.2	.43	.90	----	----	.04	----	.08	----	----	----	----	.40	----	----	.16	----	----	----	.36	.16	0.08	----	----	----	----	----	----	----	.08	----
6	5.4	.72	.55	----	.02	----	.04	----	.06	----	.15	----	----	.04	----	.01	----	.23	----	.22	.08	----	.06	.01	----	----	----	----	----	.06	.02
7	4.6	.44	.23	.07	.07	----	2.26	----	----	----	----	----	.07	----	----	.02	.01	.38	----	.22	.09	----	.18	.01	----	----	----	----	.04	.04	.08
8	2.8	.69	.64	.26	.21	----	3.14	----	.35	----	.07	----	----	----	----	.10	----	----	----	----	.15	----	.31	----	----	----	.10	----	----	.15	.11
9	7.8	.44	.23	.18	.08	----	2.82	----	----	----	.03	----	----	----	.02	----	----	----	----	----	.16	----	----	----	----	----	----	.09	----	----	.06
10	6.3	.68	.37	.18	.12	----	1.05	----	----	----	.23	----	----	----	.03	.03	.03	.03	.20	.23	.16	----	.16	----	----	----	----	----	.18	.02	.03
11	6.9	.58	.52	----	.07	.04	.14	----	----	----	----	----	----	----	----	----	----	----	.09	.06	.11	----	----	.24	----	----	----	.10	----	----	.06
12	7.1	.48	.51	.06	.04	----	1.56	----	.10	----	----	----	.03	----	.03	.09	----	----	.04	.18	.10	.04	.10	.06	----	----	----	----	----	----	.03
13	5.7	----	.31	.30	.18	----	.88	----	----	----	.07	----	.05	----	.14	----	.10	.06	----	.10	.13	.08	.15	.15	.06	----	----	----	.08	.02	.11
14	2.7	.61	.63	.30	.09	----	----	----	.15	.05	.10	----	----	----	----	----	----	----	----	----	.30	----	.20	----	----	----	----	----	.10	.10	.23

NOVEMBER DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS NOT PELLAGRA PREVENTING THROUGHOUT THE YEAR

15	4.1	0.56	0.08	0.26	0.28									0.10		0.08	0.03				0.12		0.14						0.03				
16	6.9	.46			.04					0.23	0.43		0.04				.04					0.23			0.08	0.09					0.04	
17	3.2	.80	.84		.18						.56		.13		0.05							.42	.13		.11			0.18				0.01
18	6.5	.53	.27		.08						.92											.22	.02		.12				.22			
19	5.3	.67	.36	.38	.07						.70				.16		.05					.22			.11			.05				
20	6.8	.50	.08		.19						.11		.21		.09		.13					.08	.15		.13	.12				0.04	.11	
21	3.0	.76	.52								1.50		.25		.07	.11	.28					.19	.19							.05		.06
22	2.2	.32	.41		.06	0.06		0.06			.08			.31				0.12				.19	.10		.10							.02
23	4.8	.89	.36	.12							.62		.06		.13		.24			.13		.15	.27		.18							.02
24	6.5	.57	.27	.26	.08			.04	.06		.24				.38	.08	.07	.18				.09	.18		.22	.13			.02		.02	.04	
25	5.9	.58	.30		.06								.10		.11		.07					.12	.06		.08	.07					.05	.06	
26	4.6	.62	.78	.06	.03	.09					.21		.06			.05	.20	.08		.38		.09	.09		.02		0.06				.09	.08	

APRIL OR MAY DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS NOT PELLAGRA PREVENTING THROUGHOUT THE YEAR

15	4.1	0.47		0.24	0.44										0.22		0.15	0.02				0.19										
16	6.9	.41			.07							0.37			.12		.03				0.16	.06		0.08								
17	3.2	1.07		.07	.04					0.19		.74			.02		.04				.29	.13			0.13							0.01
18	6.5	.18	0.31		.02		0.38			.17		.09		0.03	.04	0.03	.01				.15	.08		.05						0.02	0.10	.02
20	6.8	.67	.26							.14		.50				.01	.04		0.03	0.40	.27			.08	.06						.16	.03
21	3.0	.86	1.04	.19						.25		.21					.06				.17	.14		.12								
23	4.8	.96	.2	.12	.05					.10		.03									.30	.02		.02			0.04					.09
24	6.5	.69	.31		.06		.05								.11	.09	.08				.15	.10		.05							.02	
25	5.9	.45			.07					.17		.45				.01			.15	.20	.12	.21		.12	.06					.04	.04	.03
26	4.6	.57	.61	.26	.01							.08		.15					.04		.08	.19		.01	.02			0.06		.08		.02
27	8.8	.78	.40	.06	.07					.11		.02				.04	.21				.18	.14		.10	.26						.12	.02
28	6.4	.54	.07		.04					.17												.18		.11								
29	6.6	1.04	.10		.08						0.10					.03		.07				.20		.06						.09	.13	

TABLE 16.—*Food supply of unaided families: Nutritive value of food used at each of two seasons by individual families with two types of diets*

NOVEMBER DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS PELLAGRA PREVENTING THROUGHOUT THE YEAR

Family No.	Nutritive value per adult unit per day in terms of—						Calories derived from—					
	Energy	Protein	Calcium	Phosphorus	Iron	Pellagra-preventing factor	Bread, flour, and cereal	Milk and cheese	Vegetables and fruit	Fat and oils	Sugars	Lean meat, poultry, fish, and eggs
	Calories	*Grams*	*Grams*	*Grams*	*Gram*	*Units*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	5,634	116	0.99	2.30	0.0238	3.3	37	2	19	19	17	6
2	4,645	99	1.57	3.87	.0196	1.3	40	------	6	41	11	2
3	4,218	82	1.53	2.82	.0144	2.5	47	20	2	22	9	------
4	5,340	84	1.47	3.02	.0152	3.5	43	20	11	17	9	------
5	5,057	160	.75	3.17	.0154	2.0	79	------	3	13	------	5
6	4,236	61	.84	2.23	.0078	.6	48	------	7	40	5	------

NOVEMBER DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS NOT PELLAGRA PREVENTING THROUGHOUT THE YEAR

15	2,549	42	0.55	1.54	0.0077	0.5	73	------	3	22	------	2
16	2,137	27	.53	.88	.0069	.8	35	------	13	38	13	1
17	5,466	89	1.08	2.87	.0102	1.0	52	------	5	38	4	1
18	3,279	56	.71	1.84	.0070	1.5	42	------	13	27	7	11
19	4,135	70	.78	2.37	.0101	1.8	56	------	19	19	5	1
20	2,711	70	.65	1.50	.0089	.7	41	------	5	33	14	4
21	4,323	68	.82	2.37	.0102	1.8	46	------	18	34	------	2
22	3,103	59	.88	1.54	.0111	.9	43	4	2	44	6	1
23	4,481	52	.73	2.23	.0077	.9	47	------	9	36	7	1
24	3,981	62	.75	2.04	.0152	1.2	47	2	9	26	14	2
25	2,532	49	.75	1.84	.0072	1.0	58	------	2	27	10	3
26	3,797	94	.90	2.87	.0094	1.6	66	------	9	19	3	3

APRIL OR MAY DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS PELLAGRA PREVENTING THROUGHOUT THE YEAR

2	3,501	62	0.82	1.96	0.0121	1.4	36	3	8	32	16	5
3	3,463	79	1.18	2.09	.0126	3.2	35	26	5	18	6	10
4	3,925	75	1.16	2.56	.0200	2.2	40	14	6	25	11	4
5	4,868	89	1.35	2.27	.0145	1.0	49	3	2	45	------	1
6	3,157	61	.94	2.06	.0078	.8	55	2	3	35	4	1
7	3,657	66	1.25	2.21	.0106	2.3	35	19	2	31	10	3
8	5,430	142	2.46	4.24	.0158	4.0	52	18	2	12	10	6
9	3,221	68	1.25	2.31	.0079	2.5	45	27	1	21	------	6
10	4,528	78	1.19	2.73	.0107	1.2	47	7	3	32	6	5
11	3,186	56	.86	1.91	.0139	.3	59	1	1	23	10	6
12	3,771	59	1.02	2.13	.0113	1.0	45	13	2	32	7	1
13	3,434	60	.50	1.20	.0152	.7	37	8	7	27	16	5
14	4,561	84	.66	2.40	.0125	.5	57	------	2	27	8	6

APRIL OR MAY DATA FOR FAMILIES WHOSE FOOD SUPPLY WAS NOT PELLAGRA PREVENTING THROUGHOUT THE YEAR

15	2,663	41	0.46	1.40	0.0061	0.3	67	------	4	29	------	------
16	1,833	22	.46	1.06	.0042	.4	41	------	5	46	8	------
17	3,701	60	1.57	2.83	.0134	.8	42	------	4	42	5	------
18	2,361	33	.43	1.05	.0056	1.0	48	5	4	35	4	4
20	2,890	59	.87	2.02	.0101	.9	50	------	5	33	8	4
21	4,794	80	.85	2.80	.0109	.4	69	------	2	24	5	------
23	3,470	53	.74	2.26	.0078	.3	63	------	1	33	1	2
24	2,766	41	.61	1.71	.0051	.4	59	1	2	34	3	1
25	2,680	32	.65	1.33	.0084	.9	30	------	7	49	11	3
26	3,645	72	.90	2.15	.0118	.5	63	------	1	30	1	5
27	3,723	74	1.07	2.50	.0166	.6	55	------	2	27	14	2
28	1,974	23	.42	1.20	.0034	.1	50	------	3	37	10	------
29	2,953	63	.99	2.73	.0078	.5	63	------	3	24	4	6

TABLE 17.—*Retail price of food materials in Lee County, S. C., November, 1929, May, 1930, as reported by cooperating families* [1]

Food material	Price most frequently paid		Reported price range	
	Per pound	Other unit	Per pound	Other unit
Grain products:	*Cents*		*Cents*	
Bread	6.6	10 cents per loaf		
Flour	4.2	$1 per 24 pounds	4.2 –4.6	$1–$1.10 for 24 pounds.
Corn meal	2	25 cents per package		20–50 cents per package.
Grits	2.5	5 cents per quart		
Hominy	2.5	do		
Macaroni		10 cents per package		
Oatmeal	5			
Rice	5.5			10–15 cents per quart.
Dairy products:				
Milk, fluid whole		10 cents per quart		
Milk, dry skim	25			
Cheese	35			
Vegetables, fruits:				
Potatoes	3.3			
Sweetpotatoes	3			
Beans, dried	15			
Tomatoes		10–15 cents per can		
Beans, green string	20			20–32 cents per pound.
Peas	15.6	12.5 cents per quart		12.5–20 cents per quart.
Cabbage, collards, greens, onions, turnips.	(5)			
Corn		10 cents per can		
Vegetable soup	(10)			
Berries		15 cents per quart		
Fruit, fresh	(8)			
Fats, oils:				
Butter	40		40 –50	
Lard	12.5		12.5–20	
Bacon fat	(20)			
Pork, salt	12.5		8 –17	
Sugars:				
Sugar	7		5 –10	
Honey	(20)			
Jelly		(20 cents per pint)		
Sirup	6.4			65–85 cents per gallon.
Lean meats, fish, eggs:				
Beef, fresh	15		12.5–25	
Beef, chipped	25			
Beef, corned	25		20 –30	
Beefsteak	35			
Pork	30			
Sausage	25		25 –30	
Poultry	30			
Fish	17		14 –20	
Salt fish	8.3			
Salmon	20		10 –20	
Eggs		20 cents per dozen		

[1] Parenthesis indicates price used in calculating the money value of home-produced articles of food used by some families but not purchased by any during the period of the study. The figures used for these four items were for the summer of 1930, Washington, D. C., retail price for inexpensive grades, forms, or varieties.

TABLE 18.—*Food supply of unaided families: Average quantity and money value of food materials used per adult energy unit per day by two groups at two seasons compared with suggested low-cost adequate dietary (21)*

Food material	November data for families whose food supply was—				April or May data for families whose food supply was—				Suggested low-cost adequate dietary (21)	
	Pellagra preventing throughout the year [1]		Not pellagra preventing throughout the year [2]		Pellagra preventing throughout the year [3]		Not pellagra preventing throughout the year [3]			
	Quantity	Money value	Quantity	Money value	Quantity	Money value	Quantity	Money value	Quantity suggested	Money value
	Lbs.	*Cents*	*Lbs.*	*Cents*	*Lbs.*	*Cents*	*Lbs.*	*Cents*	*Lbs.*	*Cents*
Grain products:										
Flour	0.65	2.73	0.60	2.52	0.48	2.02	0.67	2.81	0.32	1.36
Corn meal	.75	1.50	.36	.72	.47	.94	.26	.52	.22	.39
Grits	.14	.35	.09	.22	.11	.28	.07	.18	.08	.43
Rice	.09	.50	.09	.50	.07	.38	.07	.38		
Bread, other cereal			.01	.07	.01	.07			.06	.30
Total	1.63	5.08	1.15	4.03	1.14	3.69	1.07	3.89	.68	2.48
Dairy products:										
Milk	1.02	4.74			1.29	6.00	.03	.14	1.70	7.51
Cheese	.01	.18	.01	.35	.01	.21				
Total	1.03	4.92	.01	.35	1.30	6.21	.03	.14	1.70	7.51
Vegetables, fruits:										
Potatoes			.02	.07	.09	.30	.09	.30	.10	.34
Sweetpotatoes	.71	2.13	.53	1.59	.06	.18	.01	.30	.42	1.25
Cabbage					.07	.35	.20	1.00	.08	.42
Collards	.09	.45	.07	.35						
Other greens	.01	.05	.03	.15	.06	.30	.01	.05	.04	.21
Peas	.23	.46	.08	.16	.01	.02	.04	.08		
Tomatoes	.04	.33	.03	.25	.03	.25	.02	.17	.23	1.94
Other vegetables	.08	.40	.09	.45	.05	.25	.05	.25	.19	1.91
Legumes	.03	.15	.03	.15	.01	.05	.01	.05	.03	.39
Berries	.01	.10			.07	.70	.02	.20		
Other fruit			.05	.40	.04	.32	.02	.16	.19	1.54
Total	1.20	4.07	.93	3.57	.49	2.72	.47	2.29	1.28	8.00
Fats, oils:										
Salt pork, bacon	.16	2.00	.17	2.12	.14	1.75	.14	1.75	.05	.78
Lard	.09	1.12	.11	1.33	.13	1.62	.13	1.62	.02	.32
Butter					.02	.80			.03	1.04
Total	.25	3.12	.28	3.50	.29	4.17	.27	3.37	.10	2.14
Sugars:										
Sugar	.15	1.05	.10	.70	.12	.84	.06	.42	.08	.55
Molasses, sirup	.13	.82	.03	.19	.06	.38	.04	.25	.11	.88
Preserves, jellies	.02	.13	.01	.03	.01	.03			.04	
Total	.30	2.00	.14	.92	.19	1.25	.10	.67	.23	1.43
Lean meats, fish, eggs:										
Poultry	.12	3.60	.02	.60	.01	.15			.05	1.56
Beef	.02	.30	.02	.30	.03	.45	.02	.30	.03	.39
Ham	.01	.30			.03	.90				
Fresh pork, other meat			.02	.60	.01	.30	.01	.24	.13	3.90
Fish	.08	1.36	.03	.51	.08	1.36	.04	.68	.03	.52
Eggs		.03	.01	.13	.07	.93	.02	.27	.05	.69
Total	.23	5.59	.10	2.14	.23	4.09	.09	1.49	.29	7.06
Grand total	4.64	24.78	2.61	14.51	3.64	22.13	2.03	11.85	4.28	28.62

[1] Average for 6 families. [2] Average for 12 families. [3] Average for 13 families.

TABLE 19.—*Food supply of unaided families in relation to pellagra incidence: Reported use by individual families of pellagra-preventing food materials in the late winter and spring; with history of pellagra, and pellagra incidence by sex and age groups in the late spring*

FAMILIES WHOSE FOOD SUPPLY WAS PELLAGRA PREVENTING THROUGHOUT THE YEAR

Family No.	Reported use per capita per day of—			Period covered by report on use of food previous to last physical examination	Individuals given physical examinations periodically											
					Total				With history of pellagra				In whom pellagra was observed in late spring			
	Milk	Vegetables, and fruit	Lean meat, fish, and eggs		Men	Women	Boys	Girls	Men	Women	Boys	Girls	Men	Women	Boys	Girls
	Cups	*Pound*	*Pound*	*Weeks*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
1	3.3	0.23	0.08	14		2	2			2				[1] 1		
2	.1	.18	.30	4	1	1	2		1		1					
3	2.1	.15	.22	12	1	2	1	3	1	1		1				[1] 1
4	3.9	.20	.11	14		1	3	6								
5	.2	.14	.42	12	1	1			1							
6	.6	.11	.12	16	1	2	2		1	1						
7	3.1	.21	.24	12		1	1	2								
8	4.0	.10	.26	10		1										
9	4.1	.18	.13	12	1	1	1	3								
10	2.0	.18	.07	4		1	3	3								
11	4.0	.64	.15	6		1		1								
12	2.2	.35	.01	4				2								
13	2.1	.20	.10	4	1		3	2			1					
14	0	.26	.04	4	1		2									
Average or total	2.26	.22	.16		7	14	20	22	4	4	2	1		[1] 1		[1] 1

[1] Did not drink milk.

TABLE 19.—*Food supply of unaided families in relation to pellagra incidence: Reported use by individual families of pellagra-preventing food materials in the late winter and spring; with history of pellagra, and pellagra incidence by sex and age groups in the late spring*—Continued

FAMILIES WHOSE FOOD SUPPLY WAS NOT PELLAGRA PREVENTING THROUGHOUT THE YEAR

Family No.	Reported use per capita per day of—			Period covered by report on use of food previous to last physical examination	Individuals given physical examinations periodically											
					Total				With history of pellagra				In whom pellagra was observed in late spring			
	Milk	Vegetables, and fruit	Lean meat, fish, and eggs		Men	Women	Boys	Girls	Men	Women	Boys	Girls	Men	Women	Boys	Girls
	Cups	*Pound*	*Pound*	*Weeks*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
15	0	0.13	0.03	6	1	1	4	1	1				1			
16	.02	.07	.07	18	1	1	5	1					1		3	1
17	.02	.09	.04	16	1	2										
18	.57	.07	.06	16		1	2	1		1				1		
19	.26	.07	.06	14	1	1		4		1				1		1
20	.14	.09	.09	18	1	3	2	1		2		1		1		
21	.07	.04	.06	14	1	1	1	1		1	1			1	1	
22	.65	.30	.29	18		1				1				1		
23	(2)	.07	.08	14		1	3	2		1	2			1		
24	.03	.05	.05	14		1	3	1						1		
25	.08	.15	.15	18	1	2		1	1	2		1		1		
26	.46	.32	.19	18	1	2		1		1				1		
27	(2)	.27	.32	12	1	2	1	2		1				1		
28	0	.25	.30	4	1	1	5	2	1			1	1	1	3	1
29	0	.27	.10	4	1	1	3	2	1	1			1	1	2	2
Average or total	[3].18	.15	.14		11	21	29	20	4	12	3	3	4	13	9	5

[2] Data questioned; therefore omitted.

[3] Average for 13 families.

TABLE 20.—*Food supply of aided families in relation to pellagra incidence: Kind and quantity of pellagra-preventing food materials given to individual families, history of pellagra among individuals periodically examined, and pellagra incidence, by age and sex groups, in the late spring*

FAMILIES GIVEN DRY SKIM MILK: 2 OUNCES PER PERSON PER DAY

Family No.	Period of aid previous to late spring physical examination	Individuals given periodic physical examinations											
		Total				With history of pellagra				In whom pellagra was observed in late spring			
		Men	Women	Boys	Girls	Men	Women	Boys	Girls	Men	Women	Boys	Girls
	Weeks	Number	Number	Number	Number	Number	Number	Number	Number	Number	Number	Number	Number
30	16		1	4	1		1				1		1
31	18		2				2				1		
32	18	1	1	1	3	1	1	1	3		1		
33	12		3		4		2				1		
34	16		3	1	1		3		1				
35	16		1	5	2		1	4	2				
36	16		1	2	5		1	2	3		[1] 1		
37	18		2	1			2	1					
38	8		1	3	2		[2] 1		[2] 1				
39	8		1	1	1		[2] 1		[2] 1				
Total		1	16	18	19	1	15	8	11		5		1

FAMILIES GIVEN DRY SKIM MILK: 4 OUNCES PER PERSON PER DAY

40	8		1	2	1								
41	8	1	1	1			[2] 1						
42	8		2				[2] 2						
Total		1	4	3	1		3						

FAMILIES GIVEN EVAPORATED MILK: 1 POUND PER PERSON PER DAY

43	16	1	2	1	3	1				1			
44	16	1	1	4	4	1	1	2	2		1		
45	22	1	1			1	1						
46	16	1	1	3	4	1	1	1	2	1	1		
47	24		1	3			1						
48	20		1		1		1		1		1		
49	18		3	1			3						
50	20	1	1	1	2		1	1					
51	22	1		3	2	1		1	2				
52	22	1	1	4	1	1	1	4	1		[1] 1		
53	8		1	1			[2] 1	[2] 1				[2] 1	
54	8		1				[2] 1						
55	8	1	1	3	4								
56	8		1	1	1		[2] 1	[2] 1					
Total		8	16	25	22	6	13	11	8	2	4	1	

FAMILIES GIVEN WHEAT GERM: 1 OUNCE PER PERSON PER DAY

57	16	1	1	3	2					1			
58	16	1	1	2	1		1	2	1				
59	18		1	3	2								
60	16	1	1	2	2	1	1	1	1		1		
Total		3	4	10	7	1	2	3	2	1	1		

FAMILIES GIVEN WHEAT GERM: 2 OUNCES PER PERSON PER DAY

61	8	1	2	1	2	[2] 1	[2] 1						
62	8		1	2	4				1				
63	8		3				[2] 2				2		
Total		1	6	3	6	1	3		1		2		

[1] Woman pregnant.
[2] Active pellagra in April when supplementary feeding was begun.

TABLE 20.—*Food supply of aided families in relation to pellagra incidence: Kind and quantity of pellagra-preventing food materials given to individual families, history of pellagra among individuals periodically examined, and pellagra incidence, by age and sex groups, in the late spring*—Continued

FAMILIES GIVEN CURED LEAN PORK: ½ POUND PER PERSON PER DAY

Family No.	Period of aid previous to late spring physical examination	Individuals given periodic physical examinations											
		Total				With history of pellagra				In whom pellagra was observed in late spring			
		Men	Women	Boys	Girls	Men	Women	Boys	Girls	Men	Women	Boys	Girls
	Weeks	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
64	20	1	1	1		1	1	1			1		
65	20		1		1		1		1				
66	20		2				1				2		
67	8	1	1	1		[2] 1	[2] 1						
68	8		1		2		[2] 1		[2] 2				
69	8	1	1				[2] 1				[3] 1		
Total		3	7	2	3	2	6	1	3		4		

FAMILIES GIVEN CANNED TOMATOES: 1½ PINTS PER PERSON PER DAY

70	8	1	1	1	3	[2] 1							
71	[4] 8	1	2	3	1								
Total		2	3	4	4	1							

FAMILIES GIVEN PURE DRY YEAST: 1 OUNCE PER PERSON PER DAY

72	8	1	1	4	2								
73	8	1		2	2			[2] 1	[2] 2				
Total		2	1	6	4			1	2				

[2] Active pellagra in April when supplementary feeding was begun.
[3] Much improved.
[4] Family also used 2 quarts of milk daily.

LITERATURE CITED

(1) ATWATER, W. O., and BRYANT, A. P.
1906. CHEMICAL COMPOSITION OF AMERICAN FOOD MATERIALS. U. S. Dept. Agr., Off. Expt. Stas. Bul. 28, 87 p., illus. (Rev. ed.)

(2) BENEDICT, F. G., MILES, W. R., ROTH, P., and SMITH, H. M.
1919. HUMAN VITALITY AND EFFICIENCY UNDER PROLONGED RESTRICTED DIET. 701 p., illus. Washington. (Carnegie Inst. Wash. Pub. 280.)

(3) GOLDBERGER, J.
1927. PELLAGRA, ITS NATURE AND PREVENTION. Pub. Health Rpts. [U. S.] 42:2193–2200. (Also reprint No. 1174.)

(4) ——— and SYDENSTRICKER, E.
1927. PELLAGRA IN THE MISSISSIPPI FLOOD AREA. REPORT OF AN INQUIRY RELATING TO THE PREVALENCE OF PELLAGRA IN THE AREA AFFECTED BY THE OVERFLOW OF THE MISSISSIPPI AND ITS TRIBUTARIES IN TENNESSEE, ARKANSAS, MISSISSIPPI, AND LOUISIANA IN THE SPRING OF 1927. Pub. Health Rpts. [U. S.] 42:2706–2725.

(5) ——— and TANNER, W. F.
1924. A STUDY OF THE TREATMENT AND PREVENTION OF PELLAGRA. Pub. Health Rpts. [U. S.] 39:87–107.

(6) GOLDBERGER, J., and TANNER, W. F.
1925. A STUDY OF THE PELLAGRA-PREVENTIVE ACTION OF DRIED BEANS, CASEIN, DRIED MILK, AND BREWERS' YEAST, WITH A CONSIDERATION OF THE ESSENTIAL PREVENTIVE FACTORS INVOLVED. Pub. Health Rpts. [U. S.] 40:54–80.
(7) ——— and WHEELER, G. A.
1920. THE EXPERIMENTAL PRODUCTION OF PELLAGRA IN HUMAN SUBJECTS BY MEANS OF DIET. U. S. Pub. Health Serv. Hyg. Lab. Bul. 102:7–116, illus.
(8) ——— and WHEELER, G. A.
1927. A STUDY OF THE PELLAGRA-PREVENTIVE ACTION OF THE TOMATO, CARROT, AND RUTABAGA TURNIP. Pub. Health Rpts. [U. S.] 42:1299–1306.
(9) ——— and WHEELER, G. A.
1927. A STUDY OF THE PELLAGRA-PREVENTIVE ACTION OF THE COWPEA (VIGNA SINENSIS) AND OF COMMERCIAL WHEAT GERM. Pub. Health Rpts. [U. S.] 42:2383–2391.
(10) ——— and WHEELER, G. A.
1929. A STUDY OF THE PELLAGRA-PREVENTIVE ACTION OF CANNED SALMON. Pub. Health Rpts. [U. S.] 44:2769–2771. (Also reprint No. 1332.)
(11) ——— WHEELER, G. A., LILLIE, R. D., and ROGERS, L. M.
1926. A FURTHER STUDY OF BUTTER, FRESH BEEF, AND YEAST AS PELLAGRA PREVENTIVES, WITH CONSIDERATION OF THE RELATION OF FACTOR P-P OF PELLAGRA (AND BLACK TONGUE OF DOGS) TO VITAMIN B. Pub. Health Rpts. [U. S.] 41:297–318, illus.
(12) ——— WHEELER, G. A., LILLIE, R. D., and ROGERS, L. M.
1928. A STUDY OF THE BLACKTONGUE-PREVENTIVE ACTION OF 16 FOODSTUFFS, WITH SPECIAL REFERENCE TO THE IDENTITY OF BLACKTONGUE OF DOGS AND PELLAGRA OF MAN. Pub. Health Rpts. [U. S.] 43:1385–1454. (Also reprint No. 1231.)
(13) ——— WHEELER, G. A., ROGERS, L. M., and SEBRELL, W. H.
1930. A STUDY OF THE BLACKTONGUE PREVENTIVE VALUE OF LARD, SALT PORK, DRIED GREEN PEAS, AND CANNED HADDOCK. Pub. Health Rpts. [U. S.] 45:1297–1308. (Also reprint No. 1381.)
(14) ——— WHEELER, G. A., SYDENSTRICKER, E., and KING, W. I.
1929. A STUDY OF ENDEMIC PELLAGRA IN SOME COTTON-MILL VILLAGES OF SOUTH CAROLINA. U. S. Pub. Health Serv., Hyg. Lab. Bul. 153, 85 p., illus.
(15) MONTGOMERY, E. G., and KARDELL, C. H.
1930. APPARENT PER CAPITA CONSUMPTION OF PRINCIPAL FOODSTUFFS IN THE UNITED STATES. U. S. Dept. Com., Dom. Com. Ser. 38, 51 p.
(16) RICE, P. B., and MUNSELL, H. E.
1931. THE APPROXIMATE UNITS OF VITAMIN A AND VITAMIN C IN FOODS. N. Y. Assoc. for Improving the Condition of the Poor. [6 p.]
(17) ROSE, M. S.
1927. THE FOUNDATIONS OF NUTRITION. 501 p., illus. New York.
(18) ———.
1929. A LABORATORY HANDBOOK FOR DIETETICS. Ed. 3, 269 p., illus. New York.
(19) SEBRELL, W. H.
1931. PELLAGRA: ITS PREVENTION AND CURE. Red Cross Courier 10: (1) 19–21, 24–25, illus.
(20) SHERMAN, H. C.
1927. CHEMISTRY OF FOOD AND NUTRITION. Ed. 3, rewritten and enl., 636 p., illus. New York.
(21) STIEBELING, H. K., and BIRDSEYE, M.
1931. ADEQUATE DIETS FOR FAMILIES WITH LIMITED INCOMES. U. S. Dept. Agr. Misc. Pub. 113, 16 p.
(22) UNITED STATES DEPARTMENT OF COMMERCE, BUREAU OF THE CENSUS.
1927. UNITED STATES CENSUS OF AGRICULTURE, 1925. PART II, THE SOUTHERN STATES. 1328 p., illus.
(23) WHEELER, G. A.
1931. THE PELLAGRA-PREVENTIVE VALUE OF CANNED SPINACH, CANNED TURNIP GREENS, MATURE ONIONS, AND CANNED GREEN BEANS. Pub. Health Rpts. [U. S.] 46:2663–2668.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Economics Division	HILDEGARDE KNEELAND, *Principal Home Economist, in Charge.*
Foods and Nutrition Division	HAZEL E. MUNSELL, *Senior Nutrition Chemist.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 332 OCTOBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

THE BEARING STRENGTH OF WOOD UNDER BOLTS

By GEORGE W. TRAYER

Senior Engineer, Forest Products Laboratory,[1] *Branch of Research, Forest Service*

CONTENTS

	Page
Introduction	1
Limits of the investigation	2
Character of the tests	2
Bearing parallel to the grain	2
Bearing perpendicular to the grain	3
General procedure	3
Proportional limit of a bolted joint	5
Bolt-bearing strength of wood parallel to the grain	6
Discussion of test results	6
Safe working stresses parallel to the grain for common bolts	12
Summarized procedure for calculating safe loads parallel to the grain	18
Effect of repeated loads	18
Safe working stresses parallel to the grain for bolts of high strength	20
Bolt-bearing strength of wood perpendicular to the grain	21
Discussion of test results	21
Safe working stresses perpendicular to the grain for common bolts	25
Summarized procedure for calculating safe loads perpendicular to the grain	29
Safe working stresses perpendicular to the grain for bolts of high strength	30
Bolt-bearing strength of wood at any angle with the grain	31
Formula for calculation	31
Details of design	32
One-end loading compared with two-end loading	32
Combined action of several bolts in a joint	32
Choice of bolt diameter	33
Placement of bolts in a joint	33
Centering and boring the bolt holes	36
Cross bolts	37
Condition of lumber	37
Appendix	38
Method of fitting stress curves to the data	38

INTRODUCTION

The purpose of this bulletin is to supply information essential to the proper design of bolted joints in timber construction. Safe loads for such connections, when computed by the methods given in various textbooks and handbooks now in use, differ widely. Such discrepancy is attributed to the fact that no extensive series of actual strength tests of ordinary bolted timber joints, from which safe working values might be selected with assurance, has heretofore been made. This bulletin presents the results of several hundred such tests, in which bolts of various diameters and lengths and timber of both coniferous and hardwood (broad-leaved) species were used. Working values for various types of joint connections, covering a range in direction of bolt pressure from parallel to perpendicular with respect to the grain, are presented. In addition to working stresses, details of design pertaining to such other features as the required spacing of bolts, the proper margin, and so forth are discussed.

[1] Maintained by the U. S. Department of Agriculture at Madison, Wis., in cooperation with the University of Wisconsin.

LIMITS OF THE INVESTIGATION

Substantially all the detailed information in this bulletin applies strictly to common, commercial steel bolts and must not be construed as applying to steel aircraft bolts. Several years ago the Forest Products Laboratory made a study of aircraft bolts the results of which have already been published.[2] The stress at the yield point of the common bolts tested was approximately 45,000 pounds per square inch, while that of the aircraft bolts previously tested was approximately 125,000 pounds per square inch. A discussion of the effect of such a difference in physical properties appears in the bulletin and a scheme for applying the working-stress recommendations to bolts having properties greater than those of the common bolts tested is presented.

Bolted joints are often reinforced with metal or wood dowels, keys, and other devices in order to increase their strength and efficiency. This bulletin does not give data that are directly applicable to such connections; it deals solely with bolt-bearing stresses. As this is written, however, a number of the more modern appliances used to strengthen a bolted connection are under test by the Forest Products Laboratory, in cooperation with the National Committee on Wood Utilization, and the results of these tests will ultimately be recorded and discussed.

CHARACTER OF THE TESTS

The tests made in this investigation were of two general types; in one the applied load acted in a direction parallel to the grain of the wood, and in the other it was perpendicular to the grain. In other words, the tests simulated the conditions illustrated in Figure 1, A and B. With the bearing strength for these two directions known, it is possible to calculate the bearing strength at any other angle, as illustrated by Figure 1, C, according to rules previously developed in the study of aircraft bolts already mentioned.

BEARING PARALLEL TO THE GRAIN

In practice, the splice plates used in joints, such as Figure 1, A, may be either of wood or of metal, according to choice or convenience. Both types were therefore used in the tests. The metal splice plates were one-fourth inch thick for bolts three-fourths inch or less in diameter and five-eighths inch thick for 1-inch bolts. Each wood plate was half the thickness of the main member. Two styles of test specimens are shown in Figure 2. A tensile load was applied to the metal plates of specimen A and the stick was held at its upper end by a through pin of relatively large diameter. To simplify the tests in which bolts of large diameters were employed, a compressive load was applied to the metal plates; when this was done, a small spacer block was bolted between the plates, near their ends, to help hold them in position. The application of a compressive load was found more convenient with specimens like Figure 2, B.

[2] TRAYER, G. W. BEARING STRENGTH OF WOOD UNDER STEEL AIRCRAFT BOLTS AND WASHERS AND OTHER FACTORS INFLUENCING FITTING DESIGN. Nat. Advisory Com. Aeronautics Tech. Notes 296, 25 p., illus. 1928.

BEARING PERPENDICULAR TO THE GRAIN

The connections involving a bearing perpendicular to the grain are also commonly made in two ways, as illustrated in Figure 1, B. Accordingly the test specimens simulating such joints were made in two ways, as is shown in Figure 3. In one (fig. 3, A) a tensile load acting perpendicular to the grain was applied through metal plates one-quarter inch in thickness, while in the other (fig. 3, B) a compressive load was applied through wooden members each one-half the thickness of the main piece.

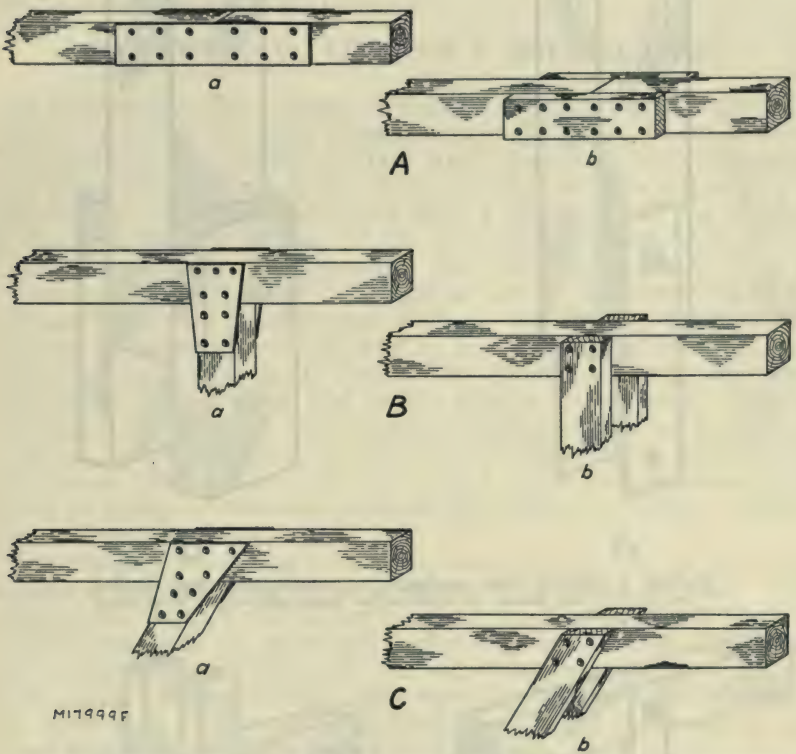


FIGURE 1.—Typical joints: A, Bearing parallel to the grain; B, bearing perpendicular to the grain; C, bearing at any angle with the grain; *a*, metal splice plates; *b*, wood splice plates or divided member

GENERAL PROCEDURE

In all tests made primarily to determine the bearing strength of wood under bolts of various diameters and lengths, only one bolt was used in each test specimen. On the other hand, in one series of tests made to determine the effect of shrinkage subsequent to assembly, four bolts were used. The specimens for this series were of green lumber, fastened with ½-inch bolts. They were put away to season after assembly and later tested with the nuts untightened. In another series of tests, made to determine the proper margin and spacing, the number of bolts in each test specimen ranged from one to eight.

Two gages were attached to each test specimen to measure the slip at each end of the bolt. The dials were graduated to thousandths of an inch. Load was applied at the rate of 0.026 inch a minute.

The bolt diameters ranged from one-quarter to 1 inch. The thickness of the main timbers ranged from 2 to 12 times the bolt

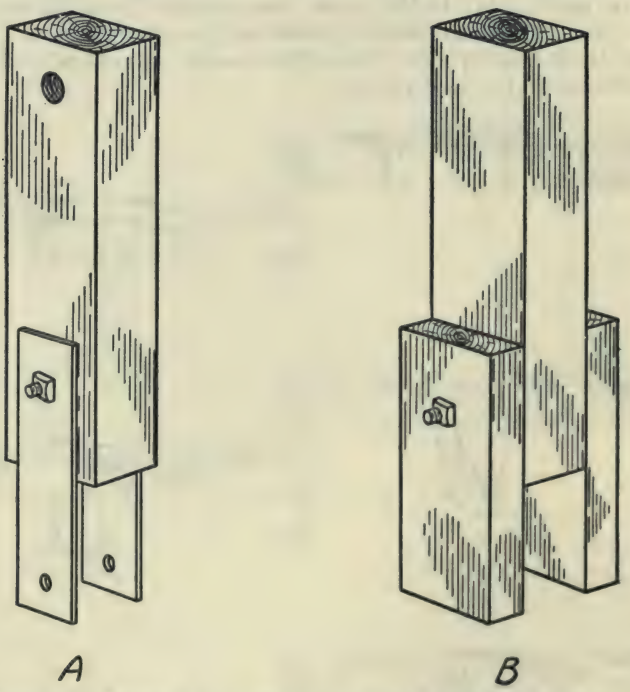


FIGURE 2.—Bolted test specimens to which load was applied parallel to the grain: A, with metal splice plates; B, with wood splice plates

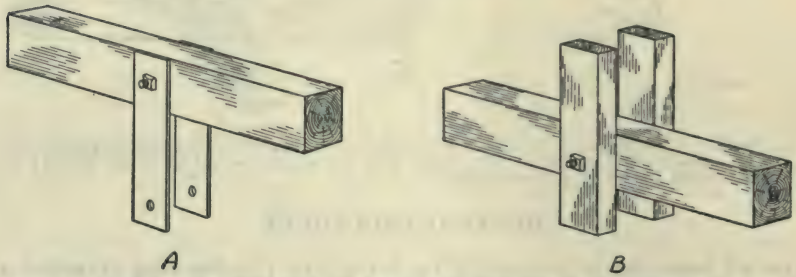


FIGURE 3.—Bolted test specimens to which load was applied perpendicular to the grain: A, With metal splice plates; B, with wood splice plates

diameters. In order to eliminate the extremely variable element of friction, at least within the proportional limit, the nuts were not drawn tight; under service conditions friction can not be relied upon because of the shrinkage that almost invariably takes place. At maximum load the bolts had usually bent enough to draw the plates snugly against the center piece, thereby introducing considerable friction.

Bolt holes in metal plates were drilled. Those in wood members were bored cleanly and perpendicular to the surfaces involved, in a direction radial to the growth rings. The results presented in this bulletin apply only to holes spaced and aligned accurately.

Five species of wood [3] were used in the tests; namely, Douglas fir, southern yellow pine, Sitka spruce, oak, and maple. In all except the one series of tests made to determine the effect of moisture changes, the test specimens were cut from seasoned lumber and the tests were conducted shortly after the joints had been assembled. The properties of the test material were determined by testing small control specimens cut from each piece.

PROPORTIONAL LIMIT OF A BOLTED JOINT

In discusssing the bearing strength of wood under bolts it is convenient to use the term proportional-limit stress, which is taken as the average stress under the bolt when the slip in the joint ceases to be proportional to the load. Although this point is regarded as a proportional limit, the joint will have a slight set on the removal of the load, chiefly because of the embedding of the bolts in the frayed wood fibers. Furthermore, the stress under the bolt is by no means uniform. What the actual stresses in the wood and in the bolt are when the proportional limit of the joint is reached is a question of academic interest, and so is the part that each plays in producing the proportional limit. The determination of the stress distribution in the wood and in the bolt is an extremely difficult mathematical problem. Approximate solutions have been obtained, as far as we are aware, only after various simplifying assumptions were made. How closely the calculated stress distributions determined by means of these assumptions agree with the actual distributions is a matter of conjecture.

The one important fact to be considered here is that at some load the slip in a bolted joint ceases to be proportional to the load. This slip is small, usually only a few hundredths of an inch. If the load at that point can be sustained repeatedly without an increase in slip or other evident injury, it can safely be regarded as a proportional limit. Repeated-load tests were made, and later discussion will show that the proportional-limit load of the joint can be sustained repeatedly without injury to the joint.

In the following discussion of the experimental study of the bolted joint the average proportional-limit stress is expressed as a ratio to a definite and known strength property of the wood. This scheme offers a simple and convenient method of obtaining safe working stresses from the results of hundreds of tests.

In presenting the test results the bearing strength of wood under bolts acting parallel to the grain is discussed first; next, the bearing strength perpendicular to the grain; and, finally, the bearing strength at any angle between these two limits. The reason for this arrangement will become apparent as the discussion proceeds.

[3] The names of species of wood in this bulletin are the standard common names employed by the Forest Service.

BOLT-BEARING STRENGTH OF WOOD PARALLEL TO THE GRAIN

DISCUSSION OF TEST RESULTS

JOINTS WITH METAL SPLICE PLATES

The joint simulated in the tests employing metal splice plates, with the load acting parallel to the grain, is represented by Figure 1, A, *a*, and the type of test specimen is that shown in Figure 2, A. The thickness of the timbers in a direction parallel to the axis of the bolt was varied in such a way that the ratio of this dimension (L) divided by the diameter of the bolt (D) was 2 for one set of specimens, 4 for the next set, and so on up to a value of 12. This definite stepping was selected for the reason that after considerable data for bolts of various diameters and lengths had been collected it became apparent that all of the results for a given value of L/D were similar for specimens of about the same quality and could be combined in an average stress figure. In other words, L/D was found to be the determining factor as regards stress. For example, the average proportional-limit stress in pounds per square inch under a ½-inch bolt in a 3-inch piece was the same as that under a 1-inch bolt in a 6-inch piece, provided the two pieces did not differ greatly in quality. This fact was also clearly demonstrated in the tests of aircraft bolts previously made.

Figure 4 is a typical curve showing the relation between load on the bolt and slip in the joint. It is for a joint made by connecting metal splice plates to a 2-inch timber by means of a single ½-inch bolt. Load was applied parallel to the grain. The points on this curve fall along a straight line up to a load of 2,800 pounds, which is taken as the proportional limit. Readings were begun after a small initial load had been applied to take up all slack, which accounts for the fact that the first point is on the axis of ordinates.

The average proportional-limit stress obtained by dividing the proportional-limit load of 2,800 pounds by the projected bearing area of the bolt, of course, was not the actual stress at this load. At the edges of the timber the stress was much greater than this value and near the center it was much less. Furthermore, when the proportional-limit load marked on Figure 4 was reached, the bolt itself had probably reached its yield point. It is likely, then, that the effects of the stresses in the wood and in the bolt were combined in producing the apparent proportional limit of the joint. In addition, it is also probable that their relative importance in this regard varies with the L/D ratio of the joint. At any rate the average proportional-limit stress was found to drop off gradually as the L/D ratio was increased.

Figure 5, B, shows the variation in average stress at the proportional limit for the softwoods tested and Figure 6, B, for the hardwoods as L/D is varied from a negligible value to 12. The average proportional-limit bearing stress under a bolt is expressed as a percentage of the maximum crushing strength of the wood in which that bolt was used. Each symbol represents the average of the re-

sults for at least four and usually five tests, except for what corresponds to zero L/D.

The stress at what corresponds to zero L/D was obtained from the test of specimens like Figure 7, A. Uniform pressure was applied to the bolt through a heavy plate in order to eliminate any bending of the bolt. The value plotted at zero L/D in Figure 5 is the average

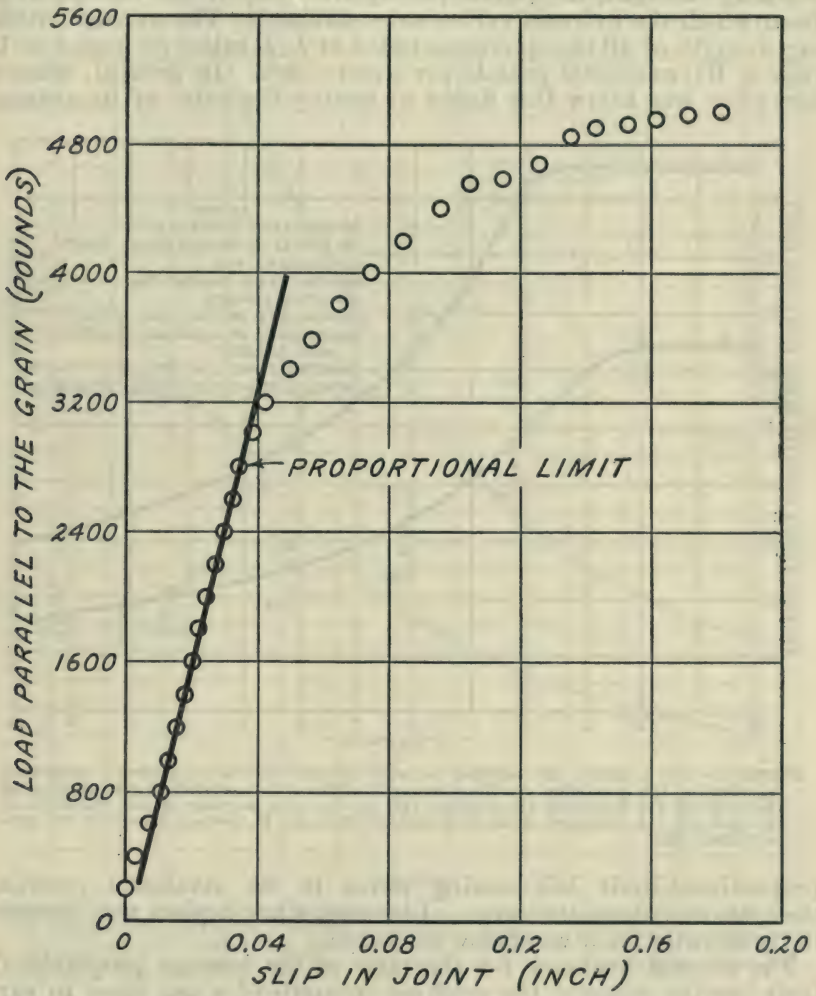


FIGURE 4.—The relation between load parallel to the grain and slip in the joint for an individual test specimen

of 55 tests, and the corresponding value in Figure 6 is the average of 50 tests.

Although a single curve was drawn through the plotted data on Figures 5 and 6, theoretically more than one curve would be required when the material in the test speciments differed markedly in quality. This statement depends upon the soundness of the previous deduction that the strengths of the bolt and of the wood are com-

bined in producing the apparent proportional-limit strength of the joint. A careful scrutiny of the plotted data may throw some light on this deduction.

Especially in curve B of Figure 5, a considerable divergence in the plotted points occurs at all L/D ratios of from 4 to 12. Immediately above and below each group of points is given the maximum crushing strength, in pounds per square inch, of the test material from which the extreme values were obtained. The average crushing strength of all the specimens tested at L/D ratios of from 4 to 12 (fig. 5, B) was 5,390 pounds per square inch. In general, when a test piece was below this figure in quality the ratio of its average

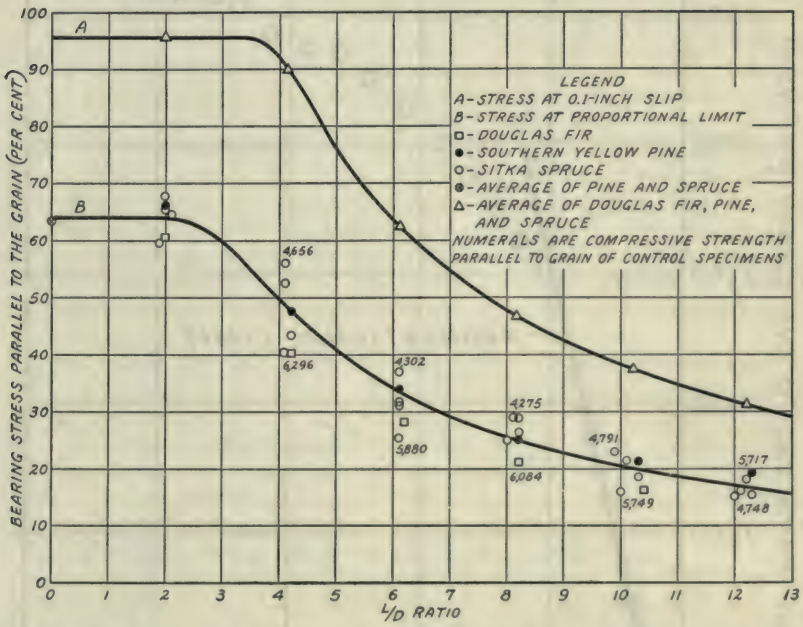


FIGURE 5.—For conifers, the relation between average bolt-bearing stress, expressed in terms of the maximum crushing strength of the wood parallel to the grain, and the ratio of the length of the bearing (L) in the main member to the diameter of the bolt (D) : A, Average stress at a slip of 0.1 inch ; B, average stress at the proportional limit

proportional-limit bolt-bearing stress to its maximum crushing strength was above the curve. Likewise, when a piece was stronger the same ratio for it was below the curve.

The general tendency for the ratio of the average proportional-limit bearing stress to the crushing strength of a test piece to vary with quality of material was even more clearly shown in the tests perpendicular to the grain. The material for such tests could well be divided into two distinct classes, one approximately double the compressive strength of the other. The results of such division appear in Figure 12. Without attempting to explain the ordinate axis of Figure 12 at this time, it may be said that the curves show the general relation between the average proportional-limit joint stress perpendicular to the grain and the L/D ratio. For a divergence in quality so extreme as this, two curves were required to rep-

resent the general trend, one for each class of material. All these facts tend to substantiate the conclusion that, except for small L/D ratios, the bending strength of the bolt as well as the crushing strength of the wood is intimately associated with the proportional-limit strength of the joint.

It so happens that beyond an L/D ratio of about 5½ the average proportional-limit stress, as represented by the B curves of Figures 5 and 6, drops off at the same rate that the L/D ratio increases.

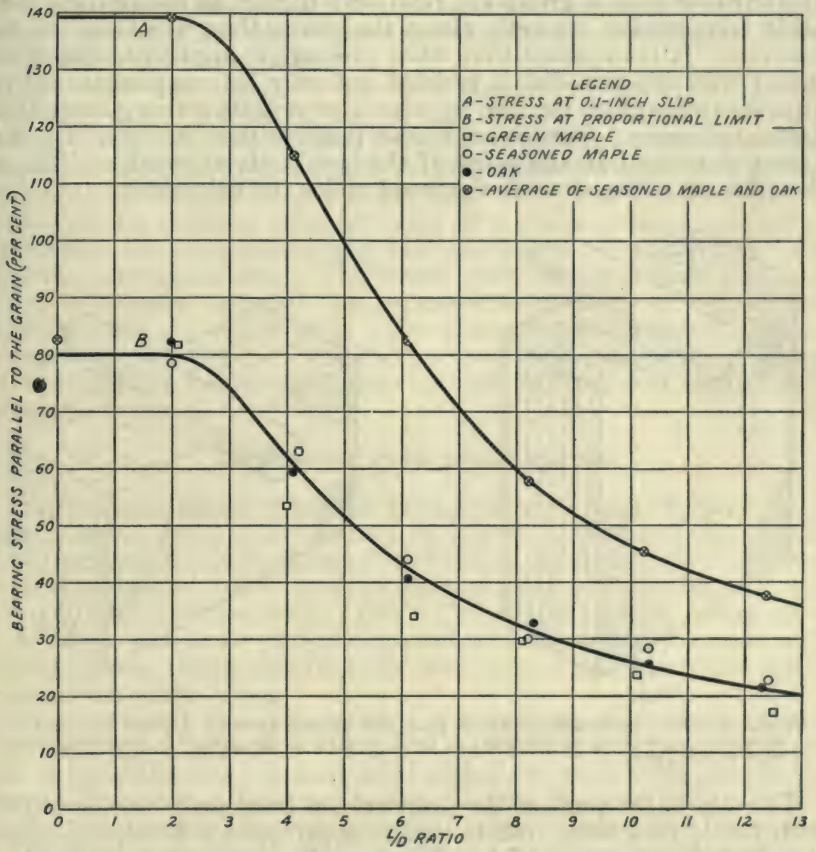


FIGURE 6.—For hardwoods, the relation between average bolt-bearing stress, expressed in terms of the maximum crushing strength of the wood parallel to the grain, and the ratio of the length of the bearing (L) in the main member to the diameter of the bolt (D) : A, Average stress at a slip of 0.1 inch ; B, average stress at the proportional limit

This means that for all L/D ratios greater than 5½ the proportional-limit load remains constant for a bolt of a given diameter.

How the curves of Figures 5 and 6 were actually fitted to the plotted data is explained in the appendix. The relationship between proportional-limit load and L/D is also shown there graphically.

Although the B curves of Figures 5 and 6 have the same general shape, the one representing the variation in average proportional-limit bolt-bearing stress with L/D for coniferous woods is lower than

the corresponding curve for hardwoods. The curve for conifers reaches only 64 per cent of the maximum crushing strength of the wood, for extremely small L/D ratios, while the one for hardwoods reaches 80 per cent. Throughout the entire L/D range this proportional difference is about the same. Only a small part of it can be accounted for by the slight difference in the average strength of the test specimens of the two groups of woods. Seemingly the significant difference is due to the fact that the across-the-grain properties of the hardwoods as a group are relatively higher, in comparison with their compressive strength along the grain, than are those of the conifers. It is apparent that when pressure is applied to the cylindrical bolt this pressure is resisted not only by components acting parallel to the grain but also by other components acting perpendicular to the grain. Further, it is also possible that, because of a different structural arrangement of the two kinds of wood, a different distribution of the stress in the wood under the bolt occurs.

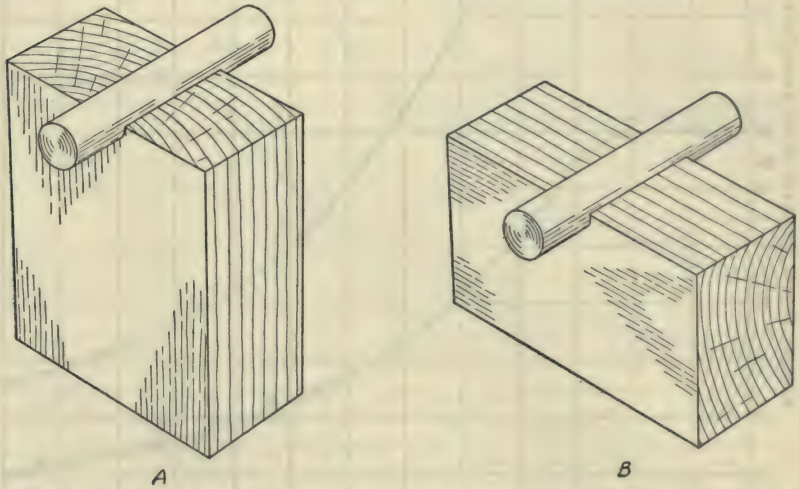


FIGURE 7.—Test specimens to which load was applied through a plate in order to eliminate all bending of the bolt: A, Load parallel to the grain; B, load perpendicular to the grain

The slip in the joint at the proportional-limit load was about 0.02 inch for ¼-inch bolts, 0.02 to 0.03 inch for ½-inch bolts, and about 0.04 inch for ¾-inch and 1-inch bolts. For any given diameter of bolt the slip at this load remained fairly constant for L/D ratios of from 4 to 12. At an L/D ratio of 2 the bending of the bolt appeared to be of little if any importance, and the slip was usually somewhat less than for larger ratios. The increase in proportional-limit slip with diameter of bolt also points to the conclusion that the bending strength of the bolt has a pronounced effect upon the proportional-limit strength of the joint, because for any given L/D ratio a large bolt must bend farther than a small one to reach a given bending stress.

The average stresses associated with a slip of 0.10 inch follow the A curves of Figures 5 and 6. These curves are higher than the B curves of the same figures, but have the same general shape. Plotting

values for still larger distortions, an upper limit of average stress is soon reached, one that is about 100 per cent of the maximum crushing strength for conifers and 140 or 150 per cent, or even more, for hardwoods. In other words, the maximum loads in the entire L/D range examined, when divided by the projected area of the bolt, yield calculated average stresses that are about equal to the crushing strength of the wood parallel to the grain for conifers and considerably greater than that strength for hardwoods. Unlike the slip at proportional limit, which remained fairly constant for all L/D ratios, however, the slip at maximum load increased greatly as the L/D ratio was made larger.

Although the strength properties of the bolt control to a considerable extent the magnitude of the proportional-limit load on a bolted joint, within the limits of the investigation the maximum load appeared to be controlled almost entirely by the strength characteristics of the wood; this fact is important. In Figure 5, B, the highest point on the curve at an L/D ratio of 4 is the average for spruce specimens the maximum compressive strength of which was 4,656 pounds per square inch. The lowest point for spruce at this L/D ratio represents material the compressive strength of which was 6,296 pounds per square inch. The average stress under the bolt at maximum load, however, was 95.8 per cent of the maximum crushing strength of the low-strength material and 93.2 per cent of the high-strength material.

JOINTS WITH WOOD SPLICE PLATES

Figure 1, A, *b*, represents the joint simulated in the tests of specimens having wood splice plates and Figure 2, B, shows the type of test specimen. The thickness of the center member was varied from 2 to 6 inches by 1-inch increments, and only one ½-inch bolt was used in each test specimen. The L/D ratio, therefore, varied from 4 to 12 in acordance with the procedure followed in the tests with metal plates. Each outside piece was always made half the thickness of the center piece.

It was found that the average proportional-limit stress values again grouped themselves along a curve like the B curves of Figures 5 and 6 and that the slip associated with these values was about 0.035 inch. The stresses, however, were somewhat less than those obtained when metal splice plates were used. Table 1 shows how the results of these tests compare with the results of corresponding tests employing metal plates. The proportional-limit values for wood plates, expressed as ratios to the crushing strengths, average 87 per cent of the corresponding metal-plate values for the two coniferous woods, and 75 per cent for the two hardwoods, over an L/D range of 4 to 12. The table discloses the fact, however, that the coniferous woods tested with metal plates averaged 23 per cent better in compressive strength than those tested with wood plates. The significance of this fact was pointed out in a foregoing statement that the ratio of the average proportional-limit stress of the joint to the maximum compressive strength of the main timber was found to be higher for a low-strength piece than for a high-strength one. This would tend to make the wood-plate values high in comparison with the metal-

plate values. The situation for the hardwoods listed in Table 1 is reversed as regards quality of material, which tends to make the wood-plate values low. It appears to be a logical conclusion that the average of the 87 and the 75 per cent ratios would very nearly represent the true relation between the average proportional-limit stresses for joints made with wood splice plates and for those made with metal splice plates. This average is 81 per cent, which for convenience will be taken as 80 per cent.

TABLE 1.—*The comparative proportional-limit strength parallel to the grain of bolted joints having wood splice plates and those having metal splice plates*

Species of wood	Ratio of bearing length of bolt in main member to diameter of bolt (L/D)	Wood splice plates		Metal splice plates		Ratio of column 4 to column 6 values
		Maximum crushing strength of main member	Proportional-limit stress of joint in terms of maximum crushing strength of main member	Maximum crushing strength of main member	Proportional-limit stress of joint in terms of maximum crushing strength of main member	
1	2	3	4	5	6	7
		Pounds per square inch		*Pounds per square inch*		
Sitka spruce	4	3,820	0.427	5,186	0.525	0.813
Do	6	4,665	.284	6,375	.311	.913
Do	8	4,038	.239	4,976	.265	.902
Do	10	4,501	.177	6,155	.187	.946
Do	12	4,141	.159	5,088	.161	.988
Southern yellow pine	4	4,809	.388	5,715	.476	.815
Do	6	5,345	.298	5,865	.340	.876
Do	8	4,950	.227	5,861	.251	.904
Do	10	4,682	.169	5,690	.212	.797
Do	12	4,959	.145	5,717	.192	.755
Average		4,591		5,663		.871
Maple	4	5,488	0.374	4,145	0.533	0.701
Do	6	5,391	.302	4,690	.340	.888
Do	8	5,866	.252	4,232	.296	.851
Do	10	6,266	.173	4,645	.237	.730
Do	12	6,616	.142	4,530	.171	.830
Oak	4	4,892	.430	4,884	.593	.725
Do	6	5,703	.290	4,096	.406	.714
Do	8	5,449	.213	4,122	.328	.649
Do	10	5,478	.181	4,450	.256	.707
Do	12	5,097	.152	4,442	.213	.714
Average		5,625		4,424		.751
Grand average		5,108		5,044		.811

SAFE WORKING STRESSES PARALLEL TO THE GRAIN FOR COMMON BOLTS

VARIATION WITH L/D

If the B curves of Figures 5 and 6 are replotted with the ordinates for extremely small L/D ratios taken as 100 per cent, both curves reduce to Figure 8, A. This curve then represents the percentage variation in average proportional-limit joint stress with variation in L/D for material not differing greatly in strength from the average of that tested. Previous discussion has indicated that, for material appreciably lower in strength than this average, the curve would

drop off less rapidly with increasing L/D ratios and for material appreciably higher in strength it would drop off more rapidly. In any event, if safe working stresses were based solely on the average proportional-limit joint stresses they would drop off with increasing L/D ratios in accordance with Figure 8, A, or at least in accordance with a slight modification of it.

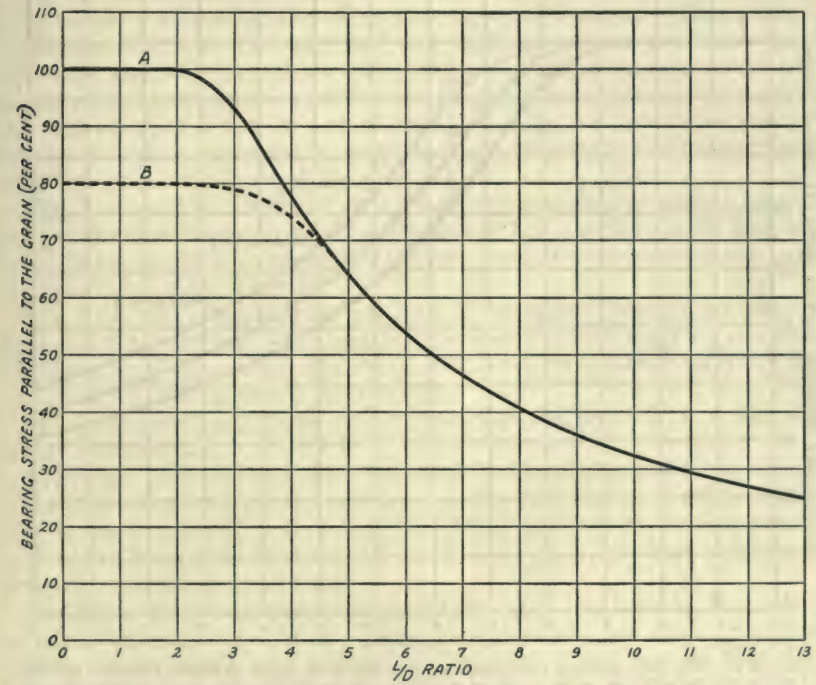


FIGURE 8.—For both conifers and hardwoods, variation in average bolt-bearing stress parallel to the grain with the ratio of the length of the bearing (L) in the main member to the diameter of the bolt (D): A, Average proportional-limit stress; B, recommended modification for actual use

It has been shown that the average stress under the bolt at maximum load does not drop off in this fashion, but remains fairly constant, which means that the gap between the proportional-limit load and the maximum load widens as L/D increases. Therefore, the same degree of safety would not be maintained at all L/D ratios if safe stresses were varied in accordance with the average proportional-limit stresses.

The Forest Products Laboratory recommends that safe bolt-bearing stresses be based largely on average proportional-limit stresses. In order to insure sufficient safety at small L/D ratios, however, the curve representing variation in safe stress should be below the curve representing variation in average proportional-limit stress at small L/D ratios, although coinciding with it in the greater L/D ratios. The modification can best be explained by referring again to Figure 8, A. This curve is dropped 20 per cent from its starting point to an L/D ratio of 2 and is dropped a proportionately less amount from there to an L/D of 5. From this point on no change is made. The new curve, Figure 8, B, consisting of the dotted portion on the left

and the full line on the right, represents the recommended variation in working stress. The curve can be more conveniently used if the scheme of reducing it to a percentage basis is again followed and the extreme left-hand portion, now 80 per cent, is taken as 100 per cent. Figure 9, C, shows the curve changed to this basis.

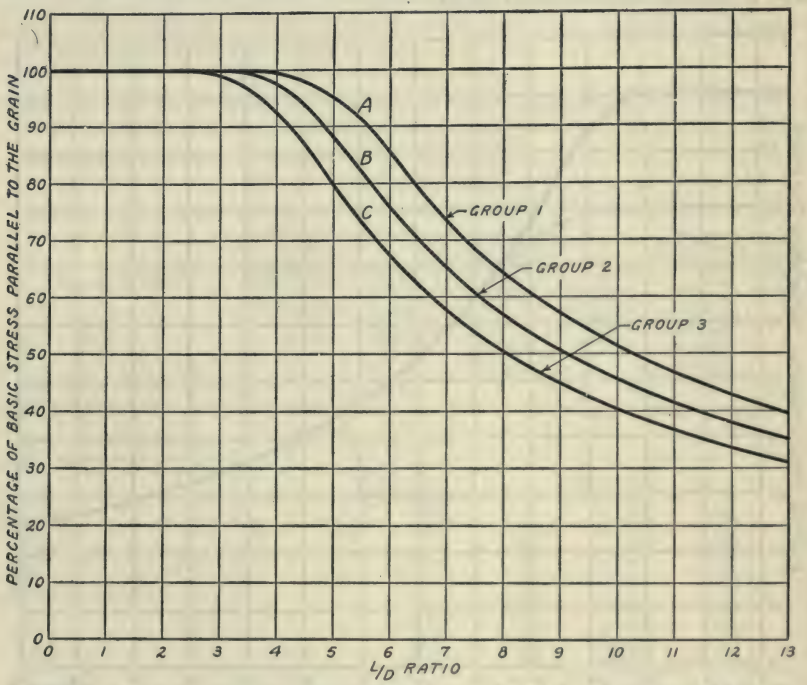


FIGURE 9.—The percentages recommended for use with basic stresses parallel to the grain in calculating safe working stresses for both conifers and hardwoods of Table 2: A, group 1 woods; B, group 2 woods; C, group 3 woods

Figure 9, C, is simply a graphical representation of the proposed variation in working stress with L/D; to supply safe working stresses it must be used in conjunction with basic stresses determined in the investigation but not yet presented. The scheme for selecting basic stresses, which is proposed on page 15, introduces a factor that places the recommended safe stresses well below the proportional-limit stresses at all values of L/D. These working stresses will vary with the proportional-limit stresses, but will not even approach them in actual magnitude.

The proposed variation in working stress shown by Figure 9, C, applies only to wood having a compressive strength approximately the same as that used in the tests. The strength properties of our common woods differ widely, and for that reason this curve can not be used for all woods without modification.

Before any scheme of modification can be suggested the range in magnitude of basic stresses adopted for the different species must be considered. The stresses recommended by the Forest Products Laboratory and the method of obtaining them from general strength data already published by the laboratory are set forth in the following discussion,

DETERMINATION OF BASIC STRESSES

In general the scheme for arriving at basic bolt-bearing stresses parallel to the grain was to modify the average ultimate crushing strength parallel to the grain of small, clear, green specimens as indicated in the following steps:

(1) Multiplication by 0.80 for coniferous woods and by 0.75 for hardwoods to allow for the effect of long-time loading. These values, determined by the Forest Products Laboratory in previous work, represent the relation of the proportional-limit strength to the ultimate crushing strength parallel to the grain as obtained in a standard test of only a few minutes' duration. Under long-time loading failure would be expected to occur at approximately the proportional limit obtained in a test of short duration.

(2) A second multiplication by 0.80 for coniferous woods because the proportional-limit curve of Figure 5 for conifers is 20 per cent lower throughout the entire L/D range than the corresponding curve of Figure 6 for hardwoods.

(3) A further multiplication by 1.20 to allow for an increase in strength with drying. The actual increase is more than 20 per cent, but there is always some checking accompanying the seasoning that partly offsets the increase in strength.

(4) Division by 2.25 to cover both variability and a reasonable factor of safety.

Although this method was followed in general, minor departures from it were necessary in setting up stresses for particular species that have unusually low across-the-grain properties in comparison with their compressive strength along the grain, or that exhibit abnormal tendencies in drying.

In Table 2 commonly used conifers and hardwoods have been listed in three groups each. The average stress for each group obtained by following the foregoing procedure is given in the third column of the table. The stresses for bearing at right angles to the grain, given in the last column, will be discussed later.

The values of Table 2 need not be reduced for grade. However, they apply only to seasoned timbers used in a dry, inside location. Modifications necessary when the condition of service is more severe are explained in the footnote to the table.

MODIFICATION OF EXPERIMENTALLY DETERMINED CURVES FOR CLASS OF MATERIAL

A survey of the test results has shown that in the larger L/D ratios a relatively higher proportional-limit joint strength was obtained for material low in strength than for material of high strength. For this reason, in the larger L/D ratios the conifers and hardwoods of groups 1 and 2, Table 2, can be allowed percentages of their basic stresses higher than those represented by Figure 9, C, which are restricted to the group 3 woods. This curve does apply strictly to group 3 woods, because all of the test material except spruce was in that class. The spruce used, however, was selected aircraft stock having a compressive strength parallel to the grain corresponding more closely to that of the group 3 conifers than to that of either group 1 or group 2.

TABLE 2.—*Basic stresses for calculating safe loads for bolted joints*[1]

Group	Species of wood	Basic stress	
		Parallel to the grain	Perpendicular to the grain
		Pounds per square inch	*Pounds per square inch*
	Softwoods:		
1	Cedar, northern and southern white Fir, balsam and commercial white Hemlock, eastern Pine, ponderosa, sugar, northern white, and western white Spruce, Engelmann, red, Sitka, and white	800	150
2	Cedar, Alaska, Port Orford, and western red Douglas fir (Rocky Mountain type) Hemlock, western Pine, Norway	1,000	200
3	Cypress, southern Douglas fir (coast type) Larch, western Pine, southern yellow Redwood Tamarack	1,300	275
	Hardwoods:		
1	Ash, black Aspen and largetooth aspen Basswood Birch, paper Chestnut Cottonwood, black and eastern Yellow poplar	925	175
2	Maple (soft), red and silver Elm, American and slippery Gum, black, red, and tupelo Sycamore	1,200	250
3	Ash, commercial white Beech Birch, sweet and yellow Elm, rock Hickory, true and pecan Maple (hard), black and sugar Oak, commercial red and white	1,500	400

[1] These stresses, when used in conjunction with Tables 3 and 4, give safe bolt-bearing stresses. They apply to seasoned timbers used in a dry, inside location. For other conditions, reduce each stress as follows: When the timbers are occasionally wet but quickly dried, use three-fourths of the stress listed; if damp or wet most of the time, use two-thirds.

The relative position of the data plotted in Figures 5 and 12 supplies a basis for adjusting the group 3 percentages for application to the other two groups. An analysis of these data, especially those shown in Figure 12, discloses the fact that in the large L/D ratios the average proportional-limit stress for a low-strength piece is relatively higher than that of a high-strength piece, and that the order of their relative magnitude corresponds approximately to the square root of the inverse ratio of the respective crushing strengths of the two pieces. Stated in another way, if the crushing strength of one timber is half that of another timber, the average proportional-limit bolt-bearing stress of the first timber, expressed as a ratio of its own crushing strength, will be approximately the square root of two times the average proportional-limit bolt-bearing stress of the second timber, expressed as a ratio of its crushing strength. Using this as a basis of adjustment, the portions of the two upper curves of Figure 9 from an L/D of 6 to an L/D of 13 were obtained. As an illustration, the ordinates of curve A in this range are those of curve C multiplied by the square root of 1.62, since the basic stresses parallel to the grain given in Table 2 for group 3 woods are 1.62 times those of the corresponding group 1 woods.

An earlier part of this bulletin has shown that at small L/D ratios the average proportional-limit stress bears the same relation to the maximum crushing strength for all classes of material within either of the two main divisions of species. Hence no adjustment of working-stress percentages should be made for L/D ratios of about 3 and less.

In completing curves A and B of Figure 9 from an L/D of 3 to an L/D of 6, they were simply filled in to agree with the general form of the lower curve.

The three curves of Figure 9 give, for L/D ratios up to 13, the percentage correction to be applied to the basic bolt-bearing stresses, parallel to the grain, for the three groups into which the common woods have been divided. Percentages taken from these curves are listed in the left-hand portion of Table 3.

TABLE 3.—*Percentage of basic stress parallel to the grain*[1] *for calculating safe bearing stresses under bolts*

Length of bolt in main member divided by its diameter (L/D)	Percentage of basic stress for—					
	Common bolts [2]			High-strength bolts [3]		
	Group 1 woods	Group 2 woods	Group 3 woods	Group 1 woods	Group 2 woods	Group 3 woods
1.0	100.0	100.0	100.0	100.0	100.0	100.0
1.5	100.0	100.0	100.0	100.0	100.0	100.0
2.0	100.0	100.0	100.0	100.0	100.0	100.0
2.5	100.0	100.0	99.7	100.0	100.0	100.0
3.0	100.0	100.0	99.0	100.0	100.0	100.0
3.5	100.0	99.3	96.7	100.0	100.0	99.7
4.0	99.5	97.4	92.5	100.0	100.0	99.0
4.5	97.9	93.8	86.8	100.0	100.0	97.8
5.0	95.4	88.3	80.0	100.0	99.8	96.0
5.5	91.4	82.2	73.0	100.0	98.2	93.0
6.0	85.6	75.8	67.2	100.0	95.4	89.5
6.5	79.0	70.0	62.0	98.5	92.2	85.2
7.0	73.4	65.0	57.6	95.8	88.8	81.0
7.5	68.5	60.6	53.7	92.7	85.0	76.8
8.0	64.2	56.9	50.4	89.3	81.2	73.0
8.5	60.4	53.5	47.4	85.9	77.7	69.6
9.0	57.1	50.6	44.8	82.5	74.2	66.4
9.5	54.1	47.9	42.4	79.0	71.0	63.2
10.0	51.4	45.5	40.3	75.8	68.0	60.2
10.5	48.9	43.3	38.4	72.5	64.8	57.4
11.0	46.7	41.4	36.6	69.7	61.9	54.8
11.5	44.7	39.6	35.0	66.8	59.2	52.4
12.0	42.8	37.9	33.6	64.0	56.7	50.2
12.5	41.1	36.4	32.2	61.4	54.4	48.2
13.0	39.5	35.0	31.0	59.1	52.4	46.3

[1] The product of the basic stress parallel to the grain selected from Table 2 and the percentage for the particular L/D ratio and species group, taken from this table, is the safe working stress at that ratio for joints with metal splice plates. When wood splice plates are used, each one-half the thickness of the main timber, 80 per cent of this product is the safe working stress.

[2] Bolts having a yield point of approximately 45,000 pounds per square inch.

[3] Bolts having a yield point of approximately 125,000 pounds per square inch.

With the preceding explanation, Tables 2 and 3 supply the information needed to calculate the safe loads parallel to the grain for bolts of diameters and lengths that are usual in commercial work. The tabular values are solely for load applied to both ends of the bolt or bolts. The value that is safe when load is applied to only one end of a bolt is half that for 2-end application, as explained later in the discussion of details of design. Further, the safe load

on a number of bolts, regardless of comparative diameters, may be taken as the sum of their individual load capacities, provided that the bolt holes are properly centered.

SUMMARIZED PROCEDURE FOR CALCULATING SAFE LOADS PARALLEL TO THE GRAIN

A brief summary of the procedure to be followed in calculating safe working loads parallel to the grain, as described in the preceding paragraphs, follows. Loads are assumed to be applied at both ends of the bolts, by means of two metal splice plates unless allowance is made for wood splice plates.

(1) Select from Table 2 the basic stress in compression parallel to the grain for the kind of wood used and for the service condition that applies. Call this stress S_1.

(2) Calculate the L/D ratio for the part of the bolt in the main member, and for this ratio select the proper stress percentage from Table 3. Call this percentage r.

(3) Multiply the basic stress S_1 by the percentage r, and the result, S_2, is the safe working stress for the particular L/D ratio used.

(4) Multiply S_2 by the projected area of the bolt, and the result, P_1, is the safe working load for one bolt when it is applied through metal splice plates.

(5) If the load is applied through wood splice plates, each one-half the thickness of the center timber, the safe load is obtained by multiplying P_1 by 0.80.

(6) When the bolt holes are properly centered, the safe load on a number of bolts, whether of the same diameter or not, may be taken as the sum of their individual load capacities.

EXAMPLES

(1) Calculate the safe working strength of a tension joint in which two pieces of seasoned coast type Douglas fir 4 inches thick are joined end to end by means of metal splice plates and eight connecting $\frac{5}{8}$-inch common bolts; that is, four bolts on each side of the butt joint. The service condition may be classed as dry, inside location.

The basic stress as given in Table 2 is 1,300 pounds per square inch. The L/D ratio is $4 \div 0.625 = 6.4$; Table 3 gives the stress percentage for this ratio as 63.0. Therefore, the

Safe stress $S_2 = 1{,}300 \times 0.63 = 819$ pounds per square inch. Safe load P_1 for one bolt $= 819 \times 4 \times 0.625 = 2{,}048$ pounds. Safe load for four bolts $= 4 \times 2{,}048 = 8{,}192$ pounds.

(2) Calculate the safe working strength of the joint in example 1 when the splice plates are of 2-inch Douglas fir instead of metal. As before:

$P_1 = 1{,}300 \times 0.63 \times 4 \times 0.625 = 2{,}048$ pounds. Safe load for one bolt $= 0.80 \times 2{,}048 = 1{,}638$ pounds. Safe load for four bolts $= 4 \times 1{,}638 = 6{,}552$ pounds.

EFFECT OF REPEATED LOADS

Thus far the discussion has been confined to joints to which load was applied at a specified rate until a maximum was passed and the test stopped. A question as to the effect of repeated loads naturally

arises. Since in this investigation safe working loads have largely been built around proportional-limit loads, it became especially important to learn whether such loads could be sustained repeatedly without appreciable increase in the slip of the joint. Accordingly, a series of tests was made on a joint in which metal splice plates were attached to a 3-inch spruce timber by means of a ½-inch bolt. The results are represented in Figure 10, C. This curve shows the accumulated set in the joint resulting from repeated loads, exclusive of that which existed when the first load was removed.

The slip associated with the first proportional-limit loading was approximately 0.025 inch. When the load was removed after the first test, a set of about 0.009 inch remained. The set shown by Figure

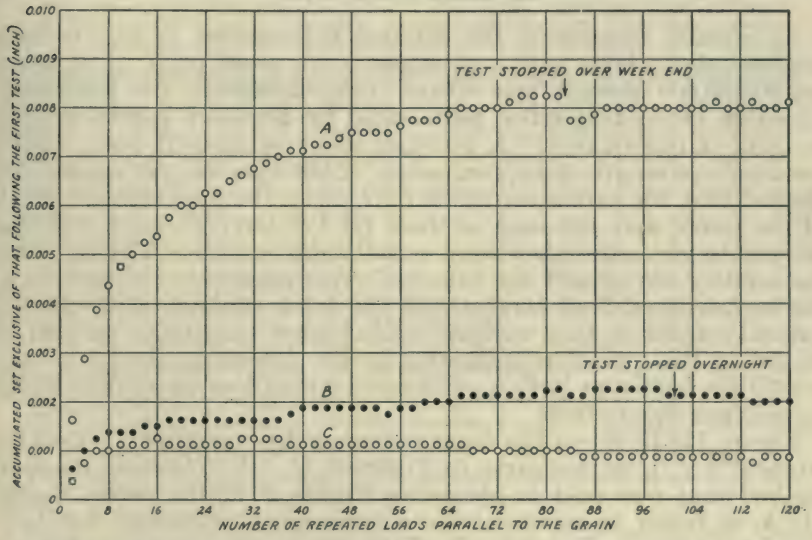


FIGURE 10.—The relation between accumulated set in a joint of spruce and number of repeated loads parallel to the grain: A, Loads 50 per cent greater than the proportional limit; B, loads 25 per cent greater than the proportional limit; C, proportional-limit loads

10, C, is what accumulated in addition to this 0.009 inch as the loads were put on and removed. Only the results for every other test are shown. These results indicate clearly that no appreciable set comes from repeating proportional-limit loads.

Figure 10, B, shows the effect of repeating a load 25 per cent in excess of the proportional-limit load of a similar joint. Again the accumulated set shown is exclusive of that which remained when the first load was removed. Here the accumulated set increases very slightly.

Figure 10, A, shows the effect of repeating a load 50 per cent in excess of the proportional limit. It is apparent that repeated loads of this magnitude would soon produce harmful effects.

Another series of tests, the results of which are not recorded in Figure 10, showed that repeated proportional-limit loads, following a single overload of 50 per cent beyond the proportional limit, produced no increase in accumulated set above that which remained after

the removal of the 50 per cent overload. Still another series showed that repeated loads 25 per cent in excess of the proportional limit, following a single overload of 50 per cent beyond the proportional limit, did produce a slight increase in accumulated set beyond that which existed after the removal of the 50 per cent overload. Although the increase was extremely slight after several hundred repetitions of the load, the tendency to increase was still apparent.

The general conclusion drawn from these tests is that no harmful slippage in the joint will result from repeating the proportional-limit load, but that constant repetition of loads in excess of it may be dangerous.

SAFE WORKING STRESSES PARALLEL TO THE GRAIN FOR BOLTS OF HIGH STRENGTH

As already mentioned, the detailed information in this bulletin applies only to bolts with a strength at the yield point of approximately 45,000 pounds per square inch. Likewise, the percentage variation in working stress represented by Figure 9 applies strictly to bolts of this quality. A previous study of aircraft bolts with a yield-point strength of approximately 125,000 pounds per square inch showed that for extremely small L/D ratios the proportional limits of the joints were the same as those for low-strength bolts, but that for the larger ratios they were considerably higher. The fact that the bending strength of the bolt is of great importance in relation to the proportional-limit strength of the joint explains this. It is a natural conclusion that working loads higher than those reached by following the procedure suggested in the foregoing should be permitted for bolts that have a yield-point strength of more than 45,000 pounds per square inch.

Figure 11, B, shows the same recommended variation in working stress with L/D as that given in Figure 9, C. By following the same method that was used in obtaining Figure 9, C, the curve, Figure 11, A, is found to represent the corresponding variation for bolts that have a yield-point strength of 125,000 pounds per square inch.

Percentages taken from Figure 11, A, are listed in the right-hand portion of Table 3 for group 3 woods. Adjustments were made for the species in groups 1 and 2 according to the procedure followed for common bolts. The adjusted values also appear in the right-hand portion of Table 3. These values and the stresses of Table 2 are recommended when bolts that have a yield point of approximately 125,000 pounds per square inch are used in engineering structures other than aircraft. The whole scheme of insuring reasonable safety in a bolted joint in an airplane is different from that generally employed in other fields of construction. For this reason no one should assume that, because these high-strength bolts have been referred to as aircraft bolts, the design procedure and the working stresses would apply to that type of construction. A publication on the use of wood in this field has already been referred to.[4]

Just what the working loads should be for bolts of a quality between 45,000 and 125,000 pounds per square inch at the yield point is not known. Probably, however, no appreciable error would be introduced by direct interpolation.

[4] See footnote 2, p. 2.

BOLT-BEARING STRENGTH OF WOOD PERPENDICULAR TO THE GRAIN

DISCUSSION OF TEST RESULTS

JOINTS WITH METAL SPLICE PLATES

The joint simulated in the tests with the thrust applied perpendicularly to the grain through metal splice plates is represented by Figure 1, B, *a*, and the type of test specimen is shown in Figure 3, A. The thickness of the test specimens in the direction parallel to the axis of the bolt was varied in such a way that the ratio of this dimension (L) to the diameter of the bolt (D) was 4 for one set of specimens, 6 for the next set, and so on up to a value of 12. The

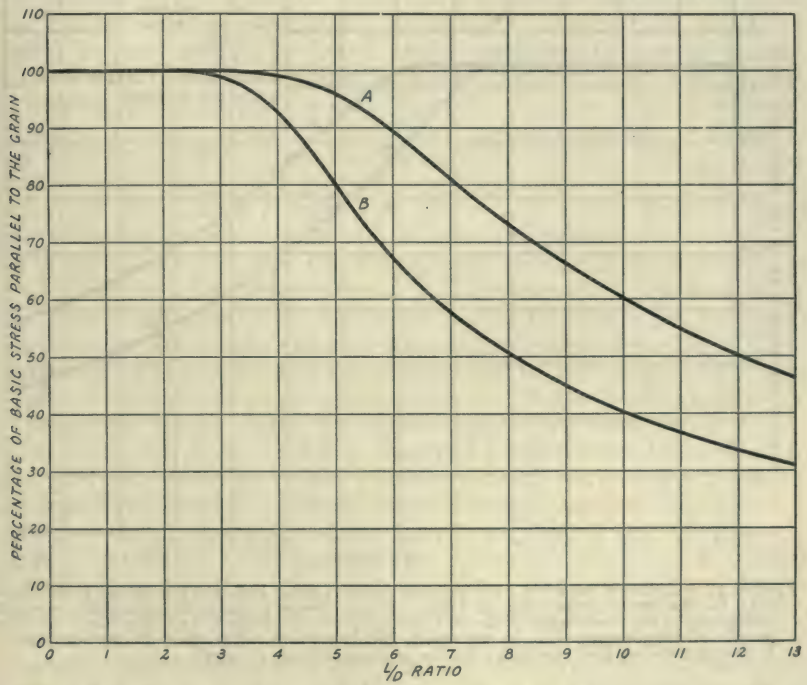


FIGURE 11.—The percentages recommended for use with basic stresses parallel to the grain in calculating safe working stresses for group 3 conifers and hardwoods of Table 2: A, For bolts having a yield point of 125,000 pounds per square inch; B, for a yield point of 45,000 pounds per square inch

tests with bearing parallel to the grain demonstrated that the L/D ratio determined the variation in the average proportional-limit stress, regardless of the diameter of the bolt. Since this fact, previously established in the tests of aircraft bolts already mentioned, was borne out conclusively in the first tests of common bolts, the tests with bearing perpendicular to the grain were limited to the one-half inch size. The variation of average stress with L/D is now so definitely established that the results may be applied with confidence to bolts of any commercial diameter.

Figure 12 shows the variation in the average stress at proportional limit in bearing perpendicular to the grain as L/D is varied from a

negligible value to 12. Each point is the average of at least four and usually five tests. The stress reported for zero L/D was obtained from tests of specimens like B of Figure 7. In Figure 12 the average proportional-limit stress under the bolt is expressed in percentage of the proportional-limit stress of control specimens tested in the usual way. Why the proportional-limit stress under a bolt may be more than 100 per cent of the proportional-limit stress of the control specimens will be explained later.

Two curves in Figure 12 were necessary to represent the variation in average proportional-limit stress with L/D, one for material relatively low in compressive strength perpendicular to the grain and

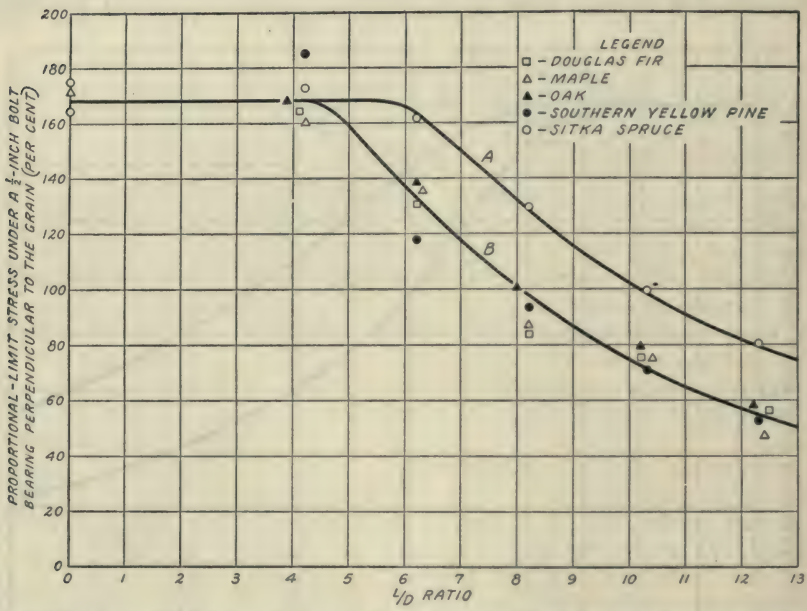


FIGURE 12.—Relation between average proportional-limit bolt-bearing stress perpendicular to the grain, expressed in terms of the proportional-limit stress of control specimens when determined under standard test procedure, and the ratio of the length of the bearing (L) in the main member to the diameter of the bolt (D): A, For species of low strength; B, for species of high strength

the other for material of greater strength in that direction. Curve A fits the test results for spruce, the control specimens of which averaged about 570 pounds per square inch for proportional-limit stress perpendicular to the grain. Curve B fits the results for southern yellow pine, coast type Douglas fir, oak, and maple, the controls of which averaged about 1,140 pounds per square inch for the same strength property.

Both these curves are similar to the B curves of Figures 5 and 6. They extend horizontally to a larger L/D before dipping downward, however, and then drop off at a slightly greater rate. This last statement is significant. As already stated, beyond a certain L/D ratio the average proportional-limit stress parallel to the grain (figs. 5 and 6) dropped off at the same rate that the L/D ratio increased, which meant that for a bolt of a given diameter the proportional-

limit load increased up to this particular L/D ratio and then remained constant. (Fig. 16, B.) The situation is somewhat different for bearing perpendicular to the grain. Here the proportional-limit load for a bolt of given diameter increased up to a certain L/D ratio and then slowly dropped off in the larger L/D range. (Fig. 17, A and B.)

The distribution of the data plotted in Figure 12 shows even more clearly than the distribution in Figure 5 that a relatively higher average proportional-limit stress is obtained with wood low in strength than with material of high strength. This in turn again points to the fact that the strength of the bolt in a measure determines the proportional-limit strength of the joint.

The slip in the joint associated with the average proportional-limit stresses plotted in Figure 12 ranged from about 0.025 to 0.030 inch.

No clearly defined maximum loads were obtained in the tests. Usually the test specimens failed under combined tension across the grain and shear, ultimately splitting and shearing from end to end. The average stress under the bolt when this type of failure occurred was much farther above the average proportional-limit stress at large L/D ratios than it was at small L/D ratios. This in a way corresponds to the greater gap between maximum stress and proportional-limit stress that obtained at large L/D ratios than at small ratios when loads were applied parallel to the grain.

In order to explain why the average proportional-limit stresses in Figure 12 exceed the proportional-limit stresses of the control specimens in some instances, it is necessary to outline briefly the standard-test procedure followed. In this procedure a plate 2 inches wide is placed across the middle of a test specimen 6 inches long, so that only 2 inches of the 6-inch length is compressed. When load is applied to the plate, the fibers along its edges are thrown into bending and tension, with the result that the observed proportional-limit stress is higher than it would be if the whole specimen were covered. Since this edge effect remains constant, the percentage increase that it causes in the average calculated stress varies as the width of plate is changed, naturally becoming greater at small widths. A similar effect is observed when the bolt diameter is varied. In order to measure this variable, a series of tests, employing bolts of various diameters and test specimens like Figure 7, B, was run. A load uniformly distributed along their length was applied to the bolts, which rested in the half-round holes. The proportional-limit stress under the bolts, expressed as a ratio to the proportional-limit stress of the material obtained by standard procedure, is shown in Figure 13. The points representing tests in which the bolt fitted loosely group themselves along the curve. The points above the curve represent snug, tight, or extremely tight fits. When a bolt fits tightly in the hole, the components of stress acting parallel to the grain, a direction in which the strength of wood is greatest, tend to raise the stress values. In actual practice, however, it would not be safe to count on any increase in stress resulting from tightness of fit. Accordingly, the curve was drawn through the lower values.

As previously stated, the tests reported in Figure 12 were made on ½-inch bolts. In this figure, the proportional-limit stress at what corresponds to zero L/D is 168 per cent of the standard pro-

portional-limit stress of the material. This agrees with the value given in Figure 13 for a bolt of the same diameter.

Although Figure 13 reports experimental results for only two species of wood, the Forest Products Laboratory recommends applying the results to all native species in commercial structural use, for this reason: These two species differ widely in their other known characteristics, covering most of the range in the mechanical prop-

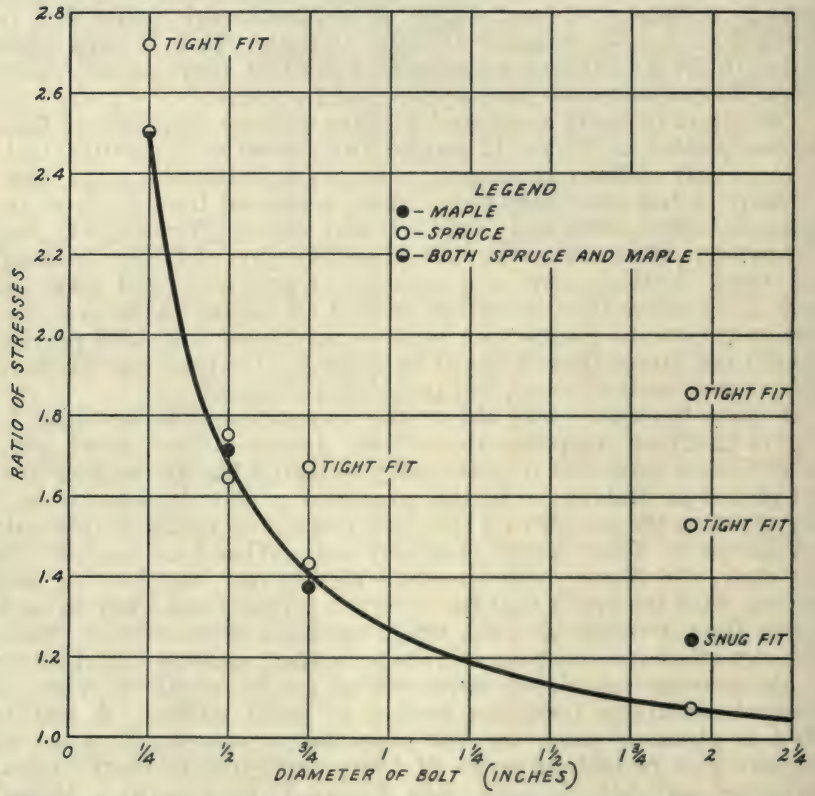


FIGURE 13.—Relation between the ratio of the proportional-limit stress perpendicular to the grain under a short bolt to the proportional-limit stress of control specimens when determined under standard test procedure, and the diameter of the bolt (D)

erties of species common in structural service, yet the test results agree closely. Two points, 2.5 for maple and 2.506 for spruce, actually coincide.

JOINTS WITH WOOD SPLICE PLATES

The joint simulated in the across-the-grain tests employing wood splice plates is represented by Figure 1, B, b, and the type of test specimen is shown in Figure 3, B. The thickness of the center member was varied from 2 to 6 inches by 1-inch increments, and ½-inch bolts were used. The L/D ratio, therefore, was varied from 4 to 12 in accordance with the procedure followed in the tests with metal

splice plates. The two outside members were always half the thickness of the center timber. It was previously found in the test of aircraft bolts bearing on the main timber perpendicular to the grain that the same average proportional-limit stresses were obtained with wood plates as with metal plates. When tests of spruce with common bolts bore out this same conclusion, therefore, no other species was tested. The tests suffice to show that no reduction in load need be made when wood splice plates are used instead of metal. It is assumed, of course, that the load on the splice plates acts parallel to the grain of the plates.

SAFE WORKING STRESSES PERPENDICULAR TO THE GRAIN FOR COMMON BOLTS

VARIATION WITH L/D

If Figure 12, B, is replotted with the ordinates for small L/D ratios taken as 100 per cent, it reduces to Figure 14, B. The transformed curve represents the percentage variation in average stress at proportional limit with L/D for material the proportional-limit stress of which, as determined by standard procedure, is approximately 1,140 pounds per square inch. Figure 12, A, replotted in the same fashion, reduces to Figure 14, A, which represents material having a proportional-limit stress of 570 pounds per square inch. If working stresses for these two classes of material were based solely on the average proportional-limit stresses under the bolts the working stresses would vary with L/D in accordance with these curves. In following such a procedure, however, the chances of failure from an overload would be greater at small L/D ratios than at the larger ratios. Therefore the Forest Products Laboratory recommends that the working-stress variation with L/D be based on a modified proportional-limit stress curve, a curve that coincides with the variation in average proportional-limit stress in the greater L/D ratios but drops below this variation in the small L/D ratios.

The scheme of modification can perhaps be explained best by referring again to Figure 14, B. In order to represent a suitable variation in safe stresses, this curve must be dropped a certain maximum amount, beginning with the axis of ordinates and extending as far as an L/D of 5, and a proportionately less amount from there to an L/D of about 7½. From this point on no change is made. The Forest Products Laboratory recommends 20 per cent for the maximum drop. The new curve, consisting of b on the left and part of B on the right, is the recommended variation in safe working stress. It is, of course, the variation for material having a proportional-limit compressive stress perpendicular to the grain of approximately 1,140 pounds per square inch. A similar change is indicated for curve A. These curves can be used more conveniently if the scheme of reducing them to a percentage basis is again followed and the extreme left-hand portion, now 80 per cent for each one, is taken as 100 per cent. The reconstructed curves are shown, respectively, in Figure 15, D and B.

Up to this point the discussion has dealt with proper variation in working stress with L/D and not with actual working stresses.

The basic stresses that are to be modified to obtain actual working stresses will be presented later.

Since there is a considerable range in the strength properties of our common woods, no single curve of variation in stress, for the reasons already given, is suitable for all. In setting up curves to apply to the various groups of species listed in Table 2, it is necessary to know the proportional-limit stress for each group. The approach to basic bolt-bearing stresses perpendicular to the grain will disclose what these proportional-limit stresses are. Before attempting to set up the stress variation applicable to each group, therefore, it will be convenient to set up the basic stresses.

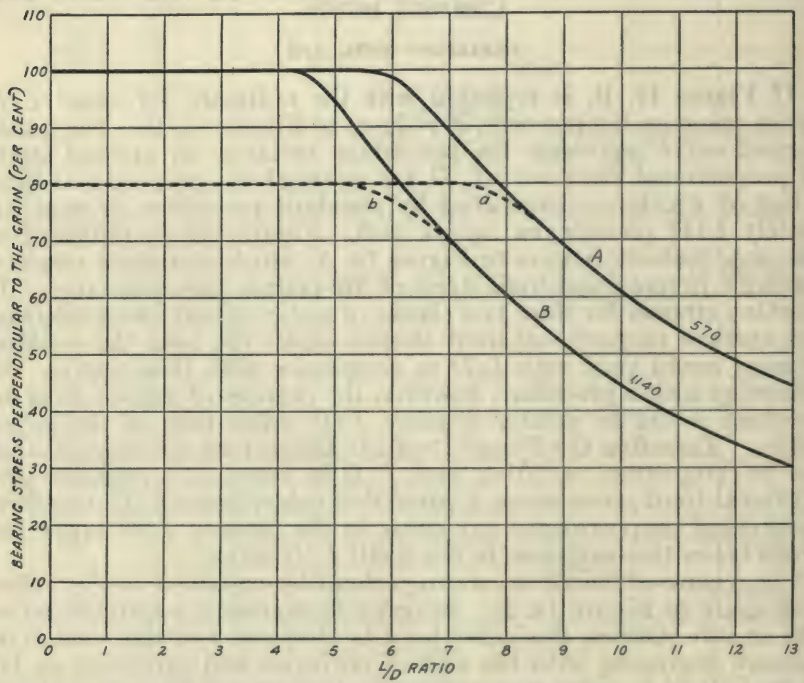


FIGURE 14.—Variation in average bolt-bearing stress perpendicular to the grain with the ratio of the length of the bearing (L) in the main member to the diameter of the bolt (D) : A, For material having a proportional-limit stress of 570 pounds per square inch ; *a*, recommended modification of curve A for actual use ; B, for material having a proportional-limit stress of 1,140 pounds per square inch ; *b*, recommended modification of curve B for actual use

DETERMINATION OF BASIC STRESSES

The general scheme of developing basic bolt-bearing stresses perpendicular to the grain from general strength data published by the Forest Products Laboratory was to modify the average proportional-limit stress perpendicular to the grain of small, clear, green specimens as indicated in the following steps:

(1) Multiplication by 1.20 to correct for an increase in strength with seasoning. The actual increase is more than 20 per cent, but

checking, which usually accompanies seasoning, tends to partly offset the increase in strength.

(2) Division by 2.25 to cover variability and factor of safety.

Minor departures from this simple scheme were necessary in setting up stresses for species that show a decided tendency to split easily or that exhibit abnormal tendencies in drying.

The scheme summarized in the preceding paragraphs may appear to provide no reduction for the effect of long-time loading. The factors, however, are applied to a proportional-limit stress, and not to a maximum stress as was done in arriving at basic stresses parallel

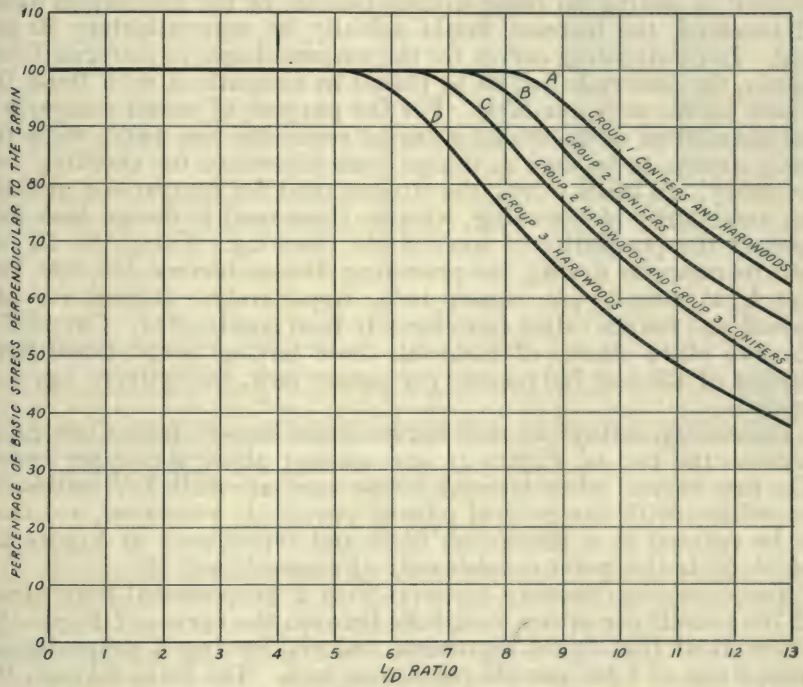


FIGURE 15.—The percentages recommended for use with basic stresses perpendicular to the grain in calculating safe working stresses for woods of Table 2: A, For group 1 conifers and hardwoods; B, for group 2 conifers; C, for group 2 hardwoods and group 3 conifers; D, for group 3 hardwoods

to the grain. This proportional-limit stress may safely be taken as the long-time maximum.

The basic stresses calculated in accordance with the general procedure outlined in the preceding are given in the last column of Table 2.

As stated in connection with the basic stresses parallel to the grain, the stresses of Table 2 need not be reduced for grade. They apply only to seasoned timbers used in a dry, inside location. This limitation intends that the timbers be seasoned prior to installation. Modifications necessary when the conditions of service are more severe are explained in the footnote to the table.

MODIFICATION OF EXPERIMENTALLY DETERMINED CURVES FOR CLASS OF MATERIAL

The proportional-limit stresses perpendicular to the grain of green specimens for the groups of wood listed in Table 2 were as follows:

	Pounds per square inch
Group 1, conifers and hardwoods	300
Group 2, conifers	375
Group 2, hardwoods, and group 3, conifers	510
Group 3, hardwoods	750

Although only 20 per cent increase in strength with drying was allowed in setting up basic stresses because of the deleterious effect of checking, the increase would actually be approximately 50 per cent. In constructing curves for the various classes of material listed herein, the materials had to be placed in comparison with those for which curves were available. For the purpose of sound comparison the assumption of no checking during seasoning was made, while for basic stresses to be used in design some allowance for checking was necessary. In other words, the stresses used for comparison avoided the uncertainty in seasoning, whereas those used in design took into account the possibility of some slight checking. Using the 50 per cent increase for drying, the preceding stresses become 450, 560, 760, and 1,125 pounds per square inch, respectively. Curves for the second and fourth values have already been constructed. Curves for the two other classes of material, those having proportional-limit stresses of 450 and 760 pounds per square inch, respectively, are still needed.

Essentially, setting up such curves means merely fitting one curve between the two of Figure 14 and another above the upper curve. The new curves, when lowered 20 per cent at small L/D ratios, in accordance with the general scheme previously employed, are then to be reduced to a percentage basis and reproduced in Figure 15, which up to this point consists only of curves B and D.

The curve representing material with a proportional-limit stress of 760 pounds per square inch falls between the curves of Figure 14. Curve B of that figure represents material having a proportional-limit stress of 1,140 pounds per square inch. The ratio between the quality of wood corresponding to curve B and that corresponding to the curve being fitted in is 1.50. In establishing ordinates for the new curve at L/D values of 11 to 13 those of the lower curve were multiplied by the square root of 1.50.

With the outer end of the curve established and the limitations that the proposed curve must be of the same general shape as those of Figure 14 and that all curves must have the same ordinate value at small L/D ratios, the curve was filled in. A similar procedure led to a curve for the material having a proportional-limit stress of 450 pounds per square inch. Both curves were then modified at small L/D ratios in accordance with the procedure already explained in detail, and were then reduced to a percentage basis. (Fig. 15, C and A.)

Percentages taken from Figure 15 are listed in Table 4. The remaining essential in the calculation of safe loads is the diameter factor, a discussion of which follows.

TABLE 4.—*Percentages of basic stress perpendicular to the grain used in calculating safe bearing stresses under bolts* [1]

Length of bolt in main member divided by its diameter (L/D)	Percentage for common bolts [2]				Percentage for high-strength bolts [3]
	Group 1 conifers and group 1 hardwoods	Group 2 conifers	Group 2 hardwoods and group 3 conifers	Group 3 hardwoods	All groups
1.0 to 5.0, inclusive	100.0	100.0	100.0	100.0	100.0
5.5	100.0	100.0	100.0	99.0	100.0
6.0	100.0	100.0	100.0	96.3	100.0
6.5	100.0	100.0	99.5	92.3	100.0
7.0	100.0	100.0	97.3	86.9	100.0
7.5	100.0	99.1	93.3	81.2	100.0
8.0	100.0	96.1	88.1	75.0	100.0
8.5	98.1	91.7	82.1	69.9	99.8
9.0	94.6	86.3	76.7	64.6	97.7
9.5	90.0	80.9	71.9	60.0	94.2
10.0	85.0	76.2	67.2	55.4	90.0
10.5	80.1	71.6	62.9	51.6	85.7
11.0	76.1	67.6	59.3	48.4	81.5
11.5	72.1	64.1	55.6	45.4	77.4
12.0	68.6	61.0	52.0	42.5	73.6
12.5	65.3	58.0	49.0	40.0	70.2
13.0	62.2	55.3	45.9	37.5	66.9

Diameter of bolt, inches	¼	⅜	½	⅝	¾	⅞	1	1¼	1½	1¾	2	2½	3 and over
Diameter factor	2.50	1.95	1.68	1.52	1.41	1.33	1.27	1.19	1.14	1.10	1.07	1.03	1.00

[1] The safe working stress for a given value of L/D is the product of three factors; (1), the basic stress perpendicular to the grain taken from Table 2, (2) the percentage from this table, and (3) the factor for bolt diameter, also from this table. No reduction need be made when wood splice plates are used except that the safe load perpendicular to the grain should never exceed the safe load parallel to the grain for any given size and quality of bolt and timber.

[2] Bolts having a yield point of approximately 45,000 pounds per square inch.

[3] Bolts having a yield point of approximately 125,000 pounds per square inch.

CORRECTION FOR BOLT DIAMETER

In calculating the safe working stress parallel to the grain for any particular L/D ratio, it is necessary only to multiply the proper basic stress selected from the third column of Table 2 by the percentage in the proper column of Table 3 opposite the L/D ratio used. In calculating the safe working stress perpendicular to the grain, however, one additional step must be taken. The basic stress selected from the last column of Table 2 is multiplied by the percentage in the proper column of Table 4, opposite the L/D ratio used, and this product is then multiplied by the correction for bolt diameter taken from Figure 13. A list of the diameter factors is given at the bottom of Table 4.

SUMMARIZED PROCEDURE FOR CALCULATING SAFE LOADS PERPENDICULAR TO THE GRAIN

A brief summary of the procedure to be followed in calculating safe working loads perpendicular to the grain follows. Loads are assumed to be applied at both ends of the bolts.

(1) Select from Table 2 the basic stress in compression perpendicular to the grain for the kind of wood used and for the service condition that is applicable. Call this S_1.

(2) Calculate the L/D ratio for the part of the bolt in the main member and for this ratio select the proper stress percentage from Table 4. Call this percentage r.

(3) Select the diameter factor from Figure 13 or from Table 4. Call this factor v.

(4) Multiply the basic stress S_1 by the percentage r and by the diameter factor v. The result, $S_1 \times r \times v = S_2$, is the safe working stress for the particular L/D ratio used.

(5) Multiply this stress by the projected area of the bolt and the result is the safe working load, whether metal or wood splice plates are used.

EXAMPLE

Calculate the safe load on a joint such as that of Figure 1, B, *b*, if the wood is seasoned coast type Douglas fir, the condition of service dry, inside location, the thickness of the center member 4 inches, and the connecting common bolts four in number and five-eighths inch in diameter.

The basic stress from Table 2 is 275 pounds per square inch. The diameter-of-bolt factor from Table 4 is 1.52. The L/D ratio is $4 \div 0.625$ or 6.4 and the corresponding stress percentage from Table 4 is 99.6.

The safe stress is then

$$275 \times 1.52 \times 0.996 = 416 \text{ pounds per square inch.}$$

The safe load for four bolts is

$$4 \times 416 \times 4 \times 0.625 = 4{,}160 \text{ pounds.}$$

SAFE WORKING STRESSES PERPENDICULAR TO THE GRAIN FOR BOLTS OF HIGH STRENGTH

It has already been stated herein that the yield-point strength of the common bolts tested was approximately 45,000 pounds per square inch, and that bolts with a higher yield point will sustain higher loads parallel to the grain than common bolts. The same is true for bearing perpendicular to the grain. The previous study of aircraft bolts already mentioned indicates what the safe bearing stress may be for bolts having a yield point of approximately 125,000 pounds per square inch.

By following the same procedure that yielded the percentages given in the left-hand portion of Table 4 for common bolts, corresponding percentages were obtained from the aircraft bolt data. For L/D ratios of 9 and larger the percentages calculated thus were found to yield working stresses for bolts of small diameter that were greater, in certain instances, than those parallel to the grain for the same bolt. Although the proportional-limit stress under a small bolt bearing perpendicular to the grain in a species with a relatively high across-the-grain strength may, under certain conditions, be somewhat higher than the proportional-limit stress parallel to the grain, it seems inadvisable to use higher working loads across the grain than parallel to the grain. The percentages calculated from the aircraft-bolt data were therefore modified in such a way that, when used with the properties listed in Table 2, the calculated safe loads perpendicu-

lar to the grain would not be greater than those parallel to the grain for joints made with metal splice plates.

The adjusted percentages for bolts having a yield point of approximately 125,000 pounds per square inch are listed in the last column of Table 4. They apply to all groups of species listed in Table 2.

The earlier pages of this bulletin have pointed out that, when wood splice plates are used in place of steel, the safe loads parallel to the grain must be reduced 20 per cent, whereas no such reduction need be made for loads acting perpendicular to the grain. Consequently, under the conditions in which the safe load perpendicular to the grain on a joint with metal splice plates is about equal to the safe load parallel to the grain on the same kind of joint, the designer may think that the unreduced perpendicular load could be greater than the reduced parallel load if wood splice plates were used. Under these conditions, however, the limiting factor would be the capacity of the splice plates for load. In this report the assumption is made that, under all conditions, the bearing thrust in wood plates is parallel to the fibers. Because of the direction of the thrust in the splice plates, the safe load applied perpendicular to the grain of the main timber through wood splice plates can not exceed the safe load applied parallel to the grain of the main timber through similar plates. A footnote covering this limitation appears in Table 4.

BOLT-BEARING STRENGTH OF WOOD AT ANY ANGLE WITH THE GRAIN

FORMULA FOR CALCULATION

With the bearing stress parallel to the grain and that perpendicular to the grain known, the following formula is recommended for calculating the bearing stress at any angle with the grain:

$$n = \frac{pq}{p \sin^2\theta + q \cos^2\theta} \qquad (1)$$

in which

n = the unit bearing stress in a direction at inclination θ with the direction of the grain,

p = the unit bearing stress in compression parallel to the grain,

q = the unit bearing stress in compression perpendicular to the grain.

This formula was derived empirically by R. L. Hankinson from tests made for the Army Air Service on the bearing strength of wood at various angles with the grain. It was checked by the Forest Products Laboratory in tests of aircraft bolts bearing at various angles with the grain, and is recommended for common bolts without further experimental verification. A numerical example illustrating the use of this formula follows:

EXAMPLE

Calculate the safe working strength of a joint like that of Figure 1, C, *b*, in which the main timber is 4 inches thick and the side pieces 2 inches thick. Four ⅝-inch common bolts join the members, which are of seasoned coast type Douglas fir, and the joint is to be used in

a dry, inside location. The smaller angle between the side pieces and center piece is 30°.

The basic stresses shown in Table 2 are 1,300 pounds per square inch parallel to the grain and 275 pounds per square inch perpendicular to the grain. The L/D ratio is $4 \div 0.625 = 6.4$. For this ratio the stress percentage for parallel bearing from Table 3 is 63.0. A factor of 0.80 must be applied in calculating the stress parallel to the grain because wood side pieces are used. Therefore

$$p = 1{,}300 \times 0.63 \times 0.80 = 655 \text{ pounds per square inch.}$$

For an L/D ratio of 6.4 the stress percentage from Table 4 for bearing perpendicular to the grain is 99.6. The diameter of bolt factor is 1.52. No correction need be made for the fact that load is applied through wood side plates. Therefore

$$q = 275 \times 1.52 \times 0.996 = 416 \text{ pounds per square inch.}$$

The sine of 30° is 0.50 and the cosine 0.866. Therefore

$$n = \frac{655 \times 416}{(655 \times 0.25) + (416 \times 0.75)} = 572 \text{ pounds per square inch.}$$

The safe load for four bolts is

$$4 \times 572 \times 4 \times 0.625 = 5{,}720 \text{ pounds.}$$

DETAILS OF DESIGN

The tests already described and discussed were confined to the symmetrical 2-end loading of single bolts in joints of various types. They supply a fundamental basis for arriving at calculated safe loads that act in any direction with respect to the fibers in bolted timbers. In addition to this work the Forest Products Laboratory has conducted tests to obtain information about certain specific details of design, such as the proper placement of the bolts in a joint. A discussion of a number of these important details is given in the following pages.

1-END LOADING COMPARED WITH 2-END LOADING

Tests have shown that a load applied to only one end of a bolt, perpendicular to its axis, may safely be taken as half the symmetrical 2-end load for the same value of L/D. Further, if the 1-end load acts at an angle with the axis of the bolt, the component at 90 degrees with that axis may be made equal to half the 2-end load. This statement assumes, of course, that ample bearing area under the washers or plates is provided to resist the load component parallel to the axis of the bolt.

COMBINED ACTION OF SEVERAL BOLTS IN A JOINT

Tests of joints having a number of bolts of the same diameter showed that the applied load was equally distributed among the several bolts, provided the bolt holes were carefully centered.

Although no tests were made on joints in which common bolts of different diameters were used, a limited number of such tests were made with aircraft bolts. It was found that, when the ratio of the diameters was not greater than two to one, no appreciable error was introduced by assuming that the bolts shared the applied load in proportion to their individual capacities to sustain load. Considering the combined safe load of several bolts equal to the sum of their individual safe loads is therefore good practice, provided the margin and the spacing are sufficient to develop the full strength of each one.

CHOICE OF BOLT DIAMETER

Although the diameter of the bolts in a joint is determined, in a general way, by the thickness of the timbers to be connected, in any given instance a wide latitude in the choice is allowable. On the other hand, however, two important elements, efficiency and safety, indicate definitely the best part of the L/D range.

Efficiency, as defined in the appendix, means the proportional-limit load on a bolt divided by the weight of metal in the main member. As shown in this appendix, for bearing parallel to the grain the efficiency of common bolts increases with L/D until a ratio of 6 is reached, and then remains constant. For bearing perpendicular to the grain, the increase continues to a ratio of about 7, and then drops off slightly. The L/D ratios for high-strength bolts at maximum efficiency, however, are even greater than the values for common bolts.

The element of safety has already been discussed in connection with working stresses, where it was stated that the margin of safety was greater at large L/D ratios than at small ones.

From the standpoint of both efficiency and safety, therefore, a bolt diameter that will give an L/D ratio of 6 or more is desirable. Ratios somewhat less than 6, however, entail only minor loss in joint efficiency with perhaps some saving in labor.

PLACEMENT OF BOLTS IN A JOINT

LOADS PARALLEL TO THE GRAIN

ALIGNMENT

The term "a row of bolts" is convenient in describing the proper alignment of bolts in a joint. In this bulletin the term means a number of bolts placed in a line that is parallel to the direction of the applied load. Thus in Figure 1, A, the bolts in both *a* and *b* would be described as placed in two parallel rows.

In making joints such as those shown in Figure 1, A, it is preferable to place the bolts in the various rows opposite one another and not to stagger them. If staggering is used in order to permit an odd number of bolts on each side of a splice, special precaution must be taken to provide sufficient area at the critical section, as described in later paragraphs.

SPACING

The center-to-center spacing of the bolts in a row, for loads acting parallel to the grain, should be at least four times the bolt diameter. Because the shear stress in the wood is not uniform across the thick-

ness of the bolted timber, concentrating at the edges, the spacing should actually increase somewhat with the L/D ratio if the maximum capacity of the joint is to be developed. With the constant spacing of four times the bolt diameter, however, the maximum loads for L/D ratios greater than 6 will not be much below the maximum obtainable with the most favorable spacing. Further, the loads at failure will be much greater than 2.25 times the safe loads, which relationship applies in the small L/D range with optimum spacing.

The spacing between adjacent bolt rows is controlled by the reduction in area at the critical section. The critical sections of the main members in the joint shown in Figure 1, A, *a*, occur at the two bolts at the left and the two at the right. The net tension area remaining at the critical section, when coniferous woods are used, should be at least 80 per cent of the total area in bearing under all the bolts in the particular timber in question. When hardwoods are used, the net tension area at the critical section should be at least equal to the bearing area under all the bolts. Although it may appear to do so, the difference in requirements does not mean that a relatively higher tensile stress is allowed for conifers than for hardwoods. The bolt-bearing stresses of the conifers, as a group, were found to be relatively lower than those for the hardwoods. A 20 per cent correction was made for this difference in arriving at basic stresses. The preceding rule for conifers operates to prevent a like differential in the allowable tensile stress.

To illustrate the use of the rule applying to hardwoods, consider two oak timbers 3 inches thick by 4 inches wide joined end to end in a tension splice by means of plates and ½-inch bolts. With four bolts placed in two parallel rows on each side of the butt joint, the area in bearing under the bolts is 6 square inches. At the critical section there are two bolt holes, and the net area in tension is therefore 9 square inches, which is more than ample. If six bolts are similarly used in two parallel rows, the bearing area is 9 square inches, but the net area in tension at the critical section remains 9 square inches, which is again ample. If eight bolts were used in two parallel rows, the joint would be expected, under its maximum load, to fail in tension at the critical section.

If an odd number of bolts of a selected diameter are required in each half of a joint in which an even number of parallel rows are employed, desirable practice will alter the diameter of all or part of the bolts in such a way as to obtain an even number. This will avoid staggering. If staggering is resorted to, however, special precautions must be taken in determining the tension area required at the critical section. The procedure can best be explained by referring to Figure 1, A, *a*. If a seventh bolt were required in each half of the joint, usual practice would place it in the center of the timber at a longitudinal distance from the present end bolts equal to the longitudinal spacing between the other bolts. In calculating the required area at the critical section, however, the seventh bolt should be considered as placed between the last pair of bolts. This rule, of course, would be unreasonable if the odd bolt were spaced an abnormally great distance from the last pair.

The reason for requiring an assumed placement of the odd bolt between the end bolts can best be explained by referring again to

Figure 1, A, *a*. With a tensile load applied to the joint shown, the lines of tension between the bolt rows proceed uninterrupted through the main members. On the contrary, an extra bolt placed beyond the end bolts and staggered between the bolt rows interrupts these lines of tension. This requires part of the tensile stress between the bolt rows to be transmitted to the net section at the single bolt by shear. The wood under the bolts is already greatly stressed in shear and the added shear stress occasioned by the shifting of the tensile stress can not be sustained. The result is failure at a load about the same as that obtained when the odd bolt is placed between the last two.

MARGIN

By end margin is meant the distance from the end of a bolted timber to the center of the bolt hole nearest the end. By edge margin is meant the distance from the edge of the timber to the center of the nearest bolt hole.

The end margin in joints under tension acting parallel to the grain should be at least seven times the bolt diameter when coniferous woods are used and at least five times the bolt diameter when hardwoods are used. When the joint is under a compressive load the end margin may be made the same as the bolt spacing, which is four times the bolt diameter for both conifers and hardwoods.

The end margin should actually increase with L/D for the same reasons given in the discussion of spacing, but the use of a constant margin is also justified by the same reasoning that permits a constant spacing.

The edge margin for loads acting parallel to the grain should be the same whether the joint is in tension or in compression. For L/D ratios of about 5 or 6, this margin should be at least one and one-half times the bolt diameter. For ratios greater than 6, increased safety will be obtained by a margin slightly more than one and one-half times the bolt diameter. For ratios less than 5 it may be slightly less. Usual practice requires the edge margin to be half the distance between bolt rows. In most instances the area requirements at the critical section will be such that an edge margin equal to half the distance between rows will be more than sufficient to meet the preceding minimum requirements.

LOADS PERPENDICULAR TO THE GRAIN

ALIGNMENT

When load is applied perpendicular to the grain of the main member of a joint through metal splice plates, it is not necessary that the bolts in the various rows be opposite one another. In fact, it is preferable to stagger them in order to avoid splitting.

In a joint like Figure 1, B, *b*, in which two wood members are at right angles with a main timber, it is necessary to align corresponding bolts when the design load approaches the bolt-bearing capacity of the side timbers. If the design load for the main timber is much less than the bolt-bearing capacity of the side timbers, as it would be for large bolts of common steel, staggering may be employed.

SPACING

The minimum center-to-center spacing of bolts in the across-the-grain direction for loads applied perpendicular to the grain through metal splice plates need only be sufficient to permit the tightening of the nuts. For wood splice plates on a joint like Figure 1, B, *b*, the spacing is controlled by the rules applying to loads acting parallel to the grain if the design load approaches the bolt-bearing capacity of the side timbers. When the design load is less than the bolt-bearing capacity of the side timbers, the spacing may be reduced below that required to develop their maximum capacity.

The spacing required between adjacent bolt rows depends upon the L/D ratio. The only tests made to determine this spacing were confined to the placement in which the bolts in adjacent rows were opposite one another. With such placement the distance between rows should be at least two and one-half times the bolt diameter for an L/D ratio of 2, and five times the bolt diameter for L/D ratios of 6 or more. For ratios between 2 and 5 the spacing between rows may be obtained by direct interpolation. The fact that the spacing in question increases so rapidly with L/D immediately suggests the desirability of staggering to avoid splitting with loads perpendicular to the grain.

MARGIN

For loads acting perpendicular to the grain, the margin between the edge toward which the bolt pressure is acting and the bolt or bolts nearest this edge should be at least four times the bolt diameter. The margin at the opposite edge is relatively unimportant.

LOADS AT AN ANGLE WITH THE GRAIN

It is virtually impossible to set up general rules regarding the alignment, spacing, and margin of bolts to cover all possible directions of the applied load. Uniform stress in the main members and a uniform distribution of load to all the bolts, however, require that the gravity axis of the members shall pass through the center of resistance of the bolt groups. Beyond that the designer must rely upon a sense of proportion and fitness rather than upon exact calculation in applying the rules already set forth to a condition of loading that is between the limits discussed.

CENTERING AND BORING THE BOLT HOLES

In the tests upon which this report is made the holes in the splice plates were placed accurately. The holes in the main members were centered with those in the plates. All holes were bored or drilled perpendicular to the surfaces involved. The discussion in this bulletin is based upon such workmanship. Obviously the workmanship is important, especially with a group of bolts, because of the smallness of the distortions that normally accompany the loads involved. Although careful centering is important for all L/D ratios, it is especially important when small ratios are used.

The bolt holes should be of such diameter that the bolts can be driven easily. When the thickness of timbers is great this requirement may mean the boring of holes appreciably oversize. This,

however, is preferable to forcible driving, which puts initial stress in the wood, thereby lowering both the proportional-limit and the maximum loads. The use of freely clearing bits with side cutter lips will insure freedom from initial splits, which, of course, are detrimental.

CROSS BOLTS

When the load on a bolted joint acts parallel to the grain a wedge of crushed fibers usually forms under the bolts after the proportional limit has been passed. This wedge produces a cleavage action that, combined with the stress components acting perpendicular to the grain, tends to split the bolted timbers. Such splitting does not start soon enough to have any appreciable effect upon the proportional-limit load, but it often helps to determine the maximum load. Stated in another way, the first real evidence of splitting is usually associated with the maximum loads and not with loads near the proportional limit.

When load is applied perpendicular to the grain, splitting again seems to start too late to affect the proportional-limit load, but it does have a very definite effect upon the maximum load.

Seasoning after assembly may also start splitting at the bolts, and once started a split develops readily when load is applied.

For these reasons the use of cross bolts is recommended, especially when the L/D ratio is small, because under such conditions the safe load is closer to the maximum load than it is in the large L/D range, as previously pointed out.

Tests in which cross bolts were employed were insufficient to furnish rules for the size and the number required for particular joints. Cross bolts, however, can certainly be smaller than the main bolts and often only one or two are required. When a single cross bolt is used in each half of a tension joint subjected to a load acting parallel to the grain, it should be placed in the portion described earlier in this bulletin as the end margin. Preferably it should be placed close to the bolt or bolts nearest the end of the timber and it well may actually touch these bolts.

CONDITION OF LUMBER

Wood shrinks as it seasons. Across the grain the change in dimension is of considerable magnitude, although along the grain it is usually negligible. Because of the shrinkage across the grain, complications commonly arise from the use of green material in a bolted joint. In a joint like Figure 1, A, *b*, the effect of shrinkage is minimized. On the other hand, if relatively wide members are joined end to end with metal splice plates, as in Figure 1, A, *a*, splits are likely to develop at or near the bolts when shrinkage takes place. The same results are likely to occur if two or more members are bolted together in such a way that the grain of one piece is at right angles to that in the other pieces, as illustrated in Figure 1, B, *b*. If splits do develop, the loads are lowered in consequence.

To illustrate what actually happens and to obtain some measure of the reduction in load caused by such splitting, a series of tests was made. Joints of green material were assembled and then allowed to air season for a time. The joints were of the type illus-

trated by Figure 1, B, *b*, and the L/D ratios ranged from 4 to 12. The proportional-limit loads ranged from 25 to 40 per cent of what would normally be expected of the material at the time of test. The maximum loads were approximately half of what would be expected had the material been allowed to season before assembly.

For these reasons the recommended use of the stresses as listed in Table 2, or as modified for condition of service, is based on the assumption that the timbers when assembled will be approximately at the moisture condition to which they will ultimately come in use.

APPENDIX

METHOD OF FITTING STRESS CURVES TO THE DATA

The points on Figure 16, A, are the proportional-limit bolt-bearing stresses parallel to the grain, for the conifers tested, when expressed as percentages of the maximum crushing strength of the control specimens. This curve, which is a reproduction of Figure 5, B, shows graphically how these data vary with the ratio of the bearing length (L) of the bolt in the main member to the bolt diameter (D).

In placing curve A of Figure 16 it was first assumed that, at an L/D ratio of 2, very little if any bending of the bolt has taken place when the proportional-

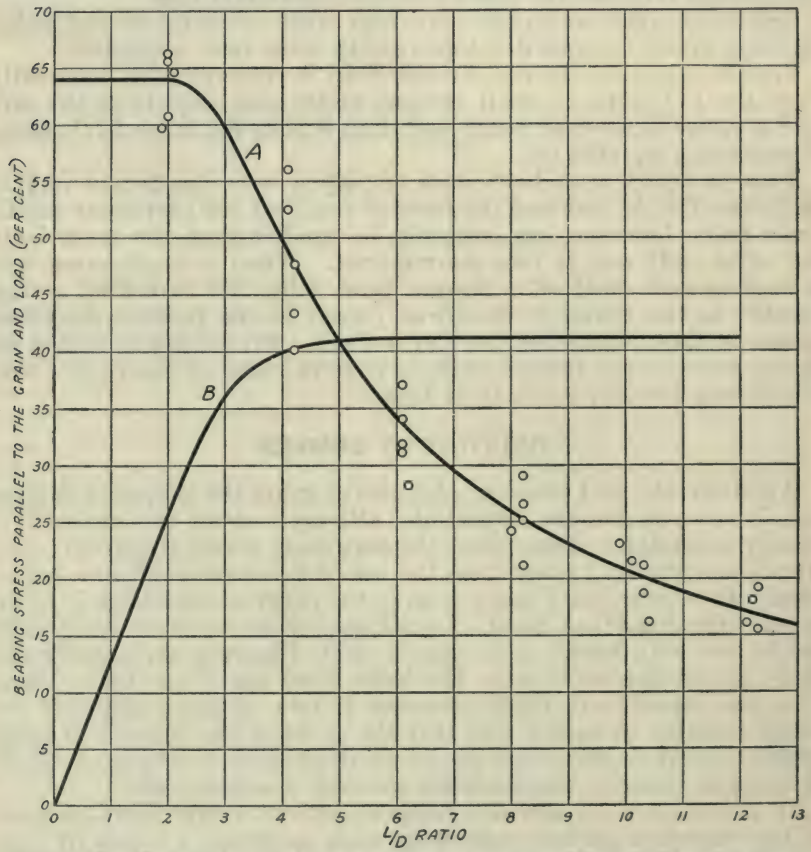


FIGURE 16.—The relationship between average proportional-limit bolt-bearing stress parallel to the grain and L/D ratio, and between proportional-limit load and length of bearing in main member for a given diameter of bolt: A, Average proportional-limit stress; B, load for a constant diameter

limit load is reached. Hence, except for experimental error, the results for an extremely small value of L/D and for a value of 2 should be the same and consequently a horizontal line can be drawn from the vertical axis to the 2 point. Continuing from there, a curve was sketched through the data points in such fashion as to either coincide with or approach closely the average of each group.

This preliminary curve was an approximate representation of the proportional-limit stress at any ratio of L to D. Consider the specific case in which D is a constant. With D a constant, the abscissas become values of L times a constant instead of L/D ratios, and the product of the stress taken from the curve and the length L is the load, except for some constant. Assuming for convenience in plotting a load curve that this constant is 0.2, the load is then

$$0.2 \times \text{stress} \times L \qquad (2)$$

The loads thus calculated follow the B curve of Figure 16. This curve increases uniformly up to an L/D ratio of 2 and then gradually fillets into a horizontal line. In addition to a logical derivation from the stress curve, the only restriction that can be placed upon this curve is that it must be smooth. At the same time the stress curve from which it was derived must not only be a smooth curve but must also fit the experimental data. After repeated trials, checking one curve against the other, the two given were obtained. They show that after an L/D ratio of about 6 has been reached, the proportional-limit load for a bolt of a given diameter remains constant.

Following this same general procedure, the curves shown in Figure 17 were developed for application to joints in which the bearing thrust was perpendicular to the grain. For this type of loading, the proportional-limit load for a bolt of a given diameter increases up to a certain L/D ratio and then drops off slightly beyond that ratio.

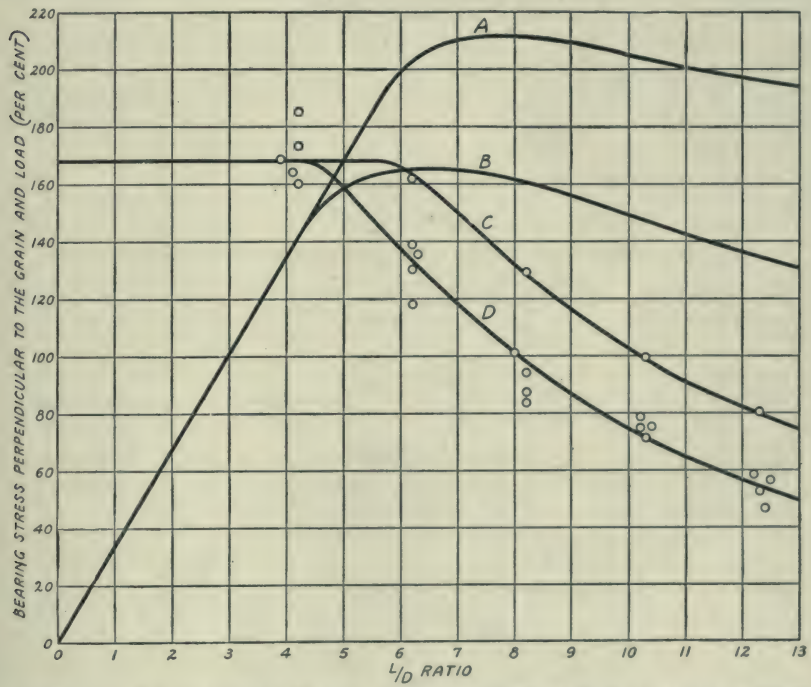


FIGURE 17.—The relationship between average proportional-limit bolt-bearing stress perpendicular to the grain and L/D ratio, and between proportional-limit load and length of bearing in main member for a given diameter of bolt: A, load for a constant diameter and stresses from curve C; B, load for a constant diameter and stresses from curve D; C, proportional-limit stress for low-strength material; D, proportional-limit stress for high-strength material

An interesting and useful relationship between efficiency and L/D ratio can be developed by assuming L to be a constant instead of D. By efficiency is meant the load divided by the weight of metal in the main member; that is, in the length L. With L constant, the load becomes stress multiplied by bolt diameter and multiplied again by some constant. The efficiency is the load divided by the product of some constant and the square of the bolt diameter. Written algebraically,

$$\text{Efficiency} = \frac{S_p \times D \times K_1}{D^2 \times K_2} = \frac{K_3 S_p}{D} = K_4 \frac{L}{D} S_p \qquad (3)$$

in which

S_p=the proportional-limit stress,
D=the diameter of the bolt,
L=the length of the bolt in the main member,
K_1, K_2, K_3, and K_4=constants.

If K_4 is taken as 0.2 for convenience, the efficiency is again expressed by equation (2).

It is obvious that values calculated by this formula and plotted against L/D would fall upon the load curves already shown in Figures 16 and 17.

The load curve of Figure 16, now presented as an efficiency curve, shows that with the length (L) fixed the efficiency increases up to an L/D of 6 and then remains constant. The corresponding curves of Figure 17, however, show that for bearing perpendicular to the grain efficiency on the basis assumed increases up to a certain L/D and then diminishes slightly.

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - Price 5 cents

TECHNICAL BULLETIN No. 331 NOVEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

PHAEOGENES NIGRIDENS WESMAEL, AN IMPORTANT ICHNEUMONID PARASITE OF THE PUPA OF THE EUROPEAN CORN BORER [1]

By H. D. SMITH

Assistant Entomologist, Division of Cereal and Forage Insects, Bureau of Entomology [2]

CONTENTS

	Page
Introduction	1
Geographical distribution	2
History	2
Systematic position	3
Host relations	3
Methods of investigation	4
Explanation of symbols used in the illustrations	5
Description	6
Adult	6
Egg	8
Larva	8
Prepupa	21
Pupa	21
Biology	21
Emergence	21
Behavior on the first day after emergence	22
Light reaction	22
Food	22
Mating	23
Oögenesis	23
Oviposition	24
Incubation	25
Larval development	26
Prepupal development	28
Pupation	29
Effect of parasite on host	29
Biology—Continued.	Page
Length of life of adult	30
Hibernation	30
Ratio of sexes	31
Parthenogenesis	32
Seasonal history	32
Armorican zone (Tours, Angers)	33
Rhodanian zone (Jura)	33
Aquitanian zone (southwestern France)	33
Mediterranean (south) zone (Hyères)	34
Padovian (Piedmont) zone (Turin)	34
Padovian (north) zone (Bergamo, Pavia, Mantova)	34
Padovian (south) zone (Piacenza, Ferrara, Sermide)	35
Venetian (low) zone (Padua)	36
Venetian (high) zone (Treviso)	36
Plavisian zone (Udine)	36
Hungarian zone	36
Hyperparasites	36
Phaeogenes nigridens as a controlling factor of *Pyrausta nubilalis*	36
Limiting factors in effectiveness of *Phaeogenes nigridens*	38
Collection and shipment of the parasite	39
Summary	42
Literature cited	44

INTRODUCTION

Phaeogenes nigridens Wesm.[3] is an internal solitary parasite which attacks the pupal stage of *Pyrausta nubilalis* Hbn. and, so far as is known at present, is the only one of any importance attacking this stage. During the years 1922 to 1928 much miscellaneous informa-

[1] The work upon which this bulletin is based was begun in the fall of 1928 at the European parasite laboratory at Hyères, Var, France, and continued with a few minor interruptions until the end of 1930.

[2] The writer gratefully acknowledges his indebtedness to H. L. Parker, under whose supervision this work was done, for valuable counsel and criticisms; to A. M. Vance, a laboratory associate, for many helpful suggestions; to Esther H. Hart for the drawing of the adult; to R. A. Cushman for the description of the species; and to W. R. Walton for assistance with the manuscript.

[3] Order Hymenoptera, superfamily Ichneumonoidea, family Ichneumonidae, subfamily Joppinae, group Joppinae cyclopneustici, tribe Phaeogenini.

tion concerning the abundance, economic importance, and biology of *Phaeogenes nigridens* was gathered by the staff of the European parasite laboratory. In the fall of 1928 the writer assumed the task of bringing to completion a detailed account of its morphology and biology and of endeavoring to breed it in large numbers in the laboratory. After completing the first part of this program and experiencing two years of only moderate success with the second phase, the results are published herein. The ultimate solution of quantity breeding may take several additional years. As shipments to the United States have been made in varying numbers since 1924, the information published herewith may prove valuable to those engaged in manipulating this parasite.

Except for numerous systematic records and a few brief biological notes, very little has been published on any species of the subfamily Joppinae. Chewyrev (*8*)[4] published some notes on *Amblyteles vadatorius* Illiger, belonging to the stenopneustic group of the Joppinae, in which he included some morphological data on the immature stages, according to Cushman (*10*). Meĭer (*16*) also published various biological data on the same species. Strickland, in his paper on the parasites of the prairie cutworm (*26*), recorded a few notes on *A. subfuscus* Cress., but he did not completely follow out its life history. Nothing has been written on the immature stages of the division Joppinae cyclopneustici, to which *Phaeogenes nigridens* belongs.

GEOGRAPHICAL DISTRIBUTION

Originally described from Belgium, this species has since been found in Sweden, Germany, and France, as cited by Dalla Torre (*11*). Recently Italy and Hungary have been added to the list. Little is known about the distribution of this parasite in Belgium, Sweden, and Germany, but in France, where a more or less intensive survey has been conducted for a number of years, it has been recovered from the following zones:[5] Aquitanian, Armorican, Rhodanian, and the Mediterranean (south). Several large collections of *Pyrausta nubilalis* have been made from the north of France in localities around Paris and Lille, but no specimens of *Phaeogenes nigridens* have ever been reared from such material. In Italy it has been found in practically all of the northern Provinces where corn or hemp is grown. In 1930 three specimens were reared by Sachtleben (*22*) from Pyrausta pupae collected at Békéscsaba, Békes County, Hungary.

Since the first shipment of this parasite to the United States in 1924, it has been recovered in satisfactory numbers from the liberation areas of Massachusetts by Jones (*15*), of the Arlington (Mass.) laboratory.

HISTORY

The earliest definite reference to this species in literature appeared in 1844, when Wesmael (*32, p. 192*) first described it as *Phaeogenes nigridens*. In 1848 (*33, p. 322*) the same writer made a more complete description of both sexes in order to correct an error previously made in his description of the male. Since then it has been redescribed by various writers.

---

[4] Italic numbers in parentheses refer to literature cited, p. 44.

[5] The names used in this bulletin are those established by Thompson and Parker (*27*).

When first reared from *Pyrausta nubilalis*, in 1922, the species was erroneously determined as *Phaeogenes planifrons* Wesm. and as such was recorded in practically all the literature until 1929, when Cushman and Roman identified it as *P. nigridens* Wesm.

It was first mentioned as a parasite of the corn borer by Caffrey and Worthley (*5*) in 1927, under the name of *Phaeogenes planifrons* Wesm. Mention was here made of its introduction and liberation in the United States in 1924. The stage of host attacked and its value as a parasite of the corn borer in Italy were also noted. Later in 1927 Poutiers (*20*) recorded it, under its correct name, as a parasite of *Tortrix pronubana* Hbn. In October of the same year Parker (*1*) listed the number of *P. nigridens* shipped to the United States during the previous fiscal year, and Jones (*14*) and Caffrey and Worthley (*6*) made short notes showing that liberations had been made in the corn borer infested areas of the United States.

In 1928 Thompson and Parker (*27*) gave a brief account of its distribution, limiting factors, extent of parasitism of the European corn borer, and life history in so far as it was known at that time. Goidanich (*13*) mentioned *P. nigridens* as parasitic on *Pyrausta nubilalis* infesting hemp in Italy, and included a few biological notes.

In 1929 Jones (15) published a brief résumé of the life history of the species, its recovery in the United States, and the total numbers of individuals shipped each year up to that time. Later in the year Parker and collaborators (*19*) recorded the extent of parasitism on Pyrausta for the years 1926 to 1928, inclusive, and gave *Phaeogenes nigridens* as the correct determination.

SYSTEMATIC POSITION

In 1894 Berthoumieu (*3, p. 505*) revised the Ichneumonidae and divided the tribe Ichneumonini into two subtribes, the stenopneustici and the cyclopneustici, based on the shape of the metathoracic spiracles. *Phaeogenes nigridens* was included in the second group, which is characterized by having round or broadly oval spiracles.

Ashmead (*2*), in 1900, gave the tribes of Berthoumieu a subfamily classification and elevated Phaeogenes to tribal rank. The subtribes of Berthoumieu were not used.

Morley (*17*), in 1903, observed the same classification as Ashmead in so far as Phaeogenes was concerned.

Schmiedeknecht (*23, p. 551*), in 1907, used a classification similar to that of Berthoumieu except that the tribes and subtribes were raised to the next higher ranks.

In 1925 Ceballos (*7, p. 60*) revised the subfamily further, giving it the name Joppinae. The two tribes used by Schmiedeknecht were no longer considered as such, being changed to groups Joppinae stenopneustici and Joppinae cyclopneustici. *Phaeogenes nigridens* remained in the latter group.

HOST RELATIONS

In addition to the corn borer the only other host from which *Phaeogenes nigridens* has been reared is *Tortrix pronubana* Hbn., a serious pest of carnations on the French and Italian Rivieras. One specimen was bred from a pupa of this species collected by Poutiers (*20*) near Antibes, France.

A closely allied species, *P. stimulator* (Grav.), has been reared from pupae of *Tortrix viridana* L. by Silvestri (*25*) in Italy, where in one year it attacked 57 per cent of its host. This species has also been reported by various authors as a primary parasite of *Hyponomeuta padella* L. and *Ellopia fasciaria* L. It is possible that *P. nigridens* may attack any one of these hosts.

P. nigridens has been found associated with the corn borer regardless of the species of plant in which the latter was living. In the Armorican zone, where no corn is grown and Artemisia is the chief food plant, the parasite is found in about the same abundance as in some of the strictly corn-growing regions. In the hemp regions of the Padovian (south) zone, where both hemp and corn are found, the parasite attacks the pupae in hemp much more severely than those in corn.

METHODS OF INVESTIGATION

In the course of many experiments, conducted in an effort to develop a suitable technic for quantity production of the parasite, the females could not be induced to oviposit with any regularity. The breeding that was accomplished, however, sufficed for a detailed study of the biology and morphology of the species.

In order to obtain Phaeogenes adults for the various breeding, longevity, and other experiments, Pyrausta pupae were collected both in the spring and in the summer. In the spring they were taken from the old cornstalks in the field, placed between layers of mulberry leaves in small cardboard boxes, and mailed to the laboratory. Upon arrival at the laboratory they were placed between fresh leaves in metal boxes with screen-wire tops. As the parasites emerged they were removed to cylindrical wire-screen cages 11 cm in diameter and 25 cm in height. Suitable hiding places were supplied by adding crumpled and corrugated paper. As food for the emerged adults sugar solution saturating a wad of cotton was attached to the side of the cage; it was renewed each week. The Pyrausta adults from unparasitized pupae were removed from the metal boxes as soon as they emerged. In the summer the parasitized pupae were placed in special small, flat boxes, which will be described later under methods of shipping. The pupae were held at about 8° C. (46.4° F.) until they reached the laboratory, when they were immediately removed and left to complete their development at room temperature. As the quantity at this time was always large, the emergence of the adults was allowed to take place in a wire-screen cage 35 by 60 by 90 cm.

Mating was accomplished either in the cylindrical cages or in vials, the latter being preferable for small-scale breeding as the female could be easily manipulated into a small space by use of the cotton stopper, thus bringing the two sexes into contact more easily and quickly. The larger the cage the longer was the time required to induce mating.

To obtain the fresh, white host pupae necessary for oviposition of the female Phaeogenes, larvae of *Pyrausta nubilalis* were collected in the fall, placed in shipping cans,[6] and allowed to spin up in the tun-

[6] These are round tin cans having two wire-screen windows and containing strips of corrugated paper tied together, like those used for the gross shipment of larvae to the Arlington (Mass.) laboratory.

nels of the corrugated-paper core. These cans were held at temperatures ranging from 5° to 10° C. (41° to 50° F.) until the following March, when the larvae were removed and occasionally wet and then dried at 25° C. (77° F.) At the end of two or three weeks prepupae appeared. These prepupae were removed, placed on moist blotting paper on the bottom of the cardboard box, and examined hourly for fresh pupae. The fresh pupae were then placed in old, half-exposed Pyrausta tunnels which had been taken from the corrugated paper cores and in which there still remained some of the larval web and the cast skin. Several of these pupae were put with a Phaeogenes female in a vial 3 by 9 cm in size. After a female had oviposited in a pupa, the latter was removed and reared in another similar vial. The humidity of the rearing cage was maintained at from 50 to 70 per cent.

In experiments with large-scale breeding, paper cores containing the overwintering larvae were placed in the cage and given the wetting and drying treatment, but the subsequent collection of the prepupae was omitted. This gave the female a more natural condition in which to work, as the hosts and their tunnels were not disturbed.

In experiments on the length of life of the adult, empty shipping cans having two wire-screen windows on each side were usually used as cages. The food consisted of weak sugar solution supplied by means of cotton plugs tied to the sides of the cage.

EXPLANATION OF SYMBOLS USED IN THE ILLUSTRATIONS

acgl, acid gland.
algl, alkaline gland.
am, anal muscles.
an, anus.
antr, antennal rudiment.
ap, apodeme or vestiges of tentorium.
aplra, anterior pleurostomal ramus or superior mandibular support.
atp, location of anterior tentorial pit.
atrac, anterior tracheal commissure.
br, brain.
ce, cephalic end.
cl, clypeus.
co, condyle.
csor, circular sensory organs.
ctrab, cephalic tracheal branches.
daphm, dorsoanterior pharyngeal muscle.
dlm, dorsal longitudinal muscles.
dom, dorsal oblique muscles.
dpphm, dorsoposterior pharyngeal muscle.
dvm, dorsoventral muscles.
dvom, dorsoventral oblique muscles.
emd, extensor muscle of mandible.
ep, epistoma.
epla, epithelial layer.
fac, fat cell.
fld, folds in skin representing weakly defined sutures.
fmd, flexor muscle of mandible.
fmlb, flexor muscle of labium.
fmlm, flexor muscle of labrum.
fmmx, flexor muscle of maxilla.
fr, frons.
fsu, frontal suture.
gc, germ cells.
glfo, glenoid fossa or cavity in which mandibular condyle articulates.
hbgf, histoblasts of female genitalia.
hbgm, histoblasts of male genitalia.
hint, hind-intestine.
ht, heart.
htra, host tracheae.
hy, hypostoma.
hypb, hypodermal branches.
1 l, *2 l*, *3 l*, histoblasts of legs.
lafd, lateral folds.
laphm, lateroanterior pharyngeal muscle.
lb, labium.
lbpl, labial palpus.
lm, labrum.
lea, lateral epicranial angle.
lom, lateral oblique muscles.
mal, Malpighian tubes.
maladr, rudiments of adult Malpighian tubes.
maoo, mature oöcyte.
md, mandible.
mesu, metopic suture.
mint, mid-intestine.
mintb, branch to mid-intestine.
mth, mouth.
mtratr, main tracheal trunk.
mx, maxilla.

mxpl, maxillary palpus.
nega, nerve ganglion.
nu, nucleus.
nc, nutritive cells.
oe, esophagus.
oo, oöcyte.
os, ostium.
ovd, oviduct.
ovl, ovariole.
ph, pharynx.
pl, pleurostoma.
poc, postocciput.
pplra, posterior pleurostomal ramus or inferior mandibular support.
psa, poison sac.
ptrac, posterior tracheal commissure.
re, rectum.
rte, rudiments of testes.
rov, rudiments of ovaries.
ru, rugosities.
se, seta.
slkd, common duct of silk glands.
slkdo, silk duct opening.
slkgl, silk gland.
slt, secondary lateral trunk.
soegng, subesophageal ganglion.
sp, spiracle.
splm, sensory protuberances of labrum.
spm, spermatheca.
spn, spines.
svm, subventral muscle.
tae, taenidium.
tefl, terminal filament.
tefo, temporal fossa.
tegng, terminal ganglion.
trac, tracheal commissure.
u, urate cell.
vade, vas deferens.
vaphm, ventroanterior pharyngeal muscle.
vlm, ventral longitudinal muscle.
vnc, ventral nerve cord.
vpphm, ventroposterior pharyngeal muscle.
vpro, ventral protuberance.
wng, histoblasts of wings.

DESCRIPTION

ADULT

EXTERNAL ANATOMY

Phaeogenes nigridens (fig. 1) is readily distinguished from the other ichneumonid parasites of the corn borer by its general robust appearance, its rusty red-brown abdomen with black anal portion, and, in the female, the white band around the middle of the antennae (fig. 1, C) and the short, slightly exserted ovipositor. The male is usually somewhat larger than the female and is easily distinguished from the latter by the absence of the white band around the antennae. (Fig. 1, B.)

As all descriptions of the adult heretofore published have been too meager and generally unsatisfactory, a new and more comprehensive description has been drawn up by R. A. Cushman, of the taxonomic unit of the Bureau of Entomology, as follows:

Female.—Length, 7 to 9 mm. Black with basal four segments of abdomen, except base of petiole, ferruginous; antennae largely ferruginous at base and black at apex with a white annulus near the middle; coxae black, legs otherwise largely ferruginous; wings hyaline, faintly stained with yellow, veins brown.

Head and thorax polished, coarsely, evenly, but not densely, punctate, the punctation becoming denser and somewhat confused on metapleura and posterior face of propodeum. Head deeply concave posteriorly, the temples strongly convex; face short, medially elevated; clypeus broad, polished, with few punctures; mandibles long, stout, nearly twice as broad at base as their distance from eyes; antennae short, stout, involute, thickened beyond middle, basal joint of flagellum little longer than thick and shorter than second.

Thorax depressed, mesoscutum and scutellum flattened; propodeum with fine but distinct carinae, the median area distinctly longer than broad; legs stout, coxae and femora distinctly punctate, hind coxae with a short, stout tooth on the under side toward apex.

Abdomen narrowly ovate, first segment polished, otherwise opaque coriaceous, segments 2 to 4 distinctly punctate, second with transverse impression near base; ovipositor extending a little beyond apex of abdomen.

Male.—Much like the female but with abdomen more slender and thorax less distinctly depressed; antennae longer, more slender, tapering toward apex, and without a white annulus; legs more largely black, the hind femur especially so, hind coxae not toothed below.

REPRODUCTIVE ORGANS OF FEMALE

The reproductive organs of the female (fig. 2) are similar to those of other ichneumonids, being composed of two long, slender ovaries, their respective genital ducts, the spermatheca, and the colleterial or accessory glands. Each ovary is about half as long as the abdomen and is composed of three polytrophic ovarioles, in the lower portion of which nutritive cells contained in distinct chambers alternate with

FIGURE 1.—*Phaeogenes nigridens:* A, Adult female; B, male antenna; C, female antenna

the developing oöcyte. Farther up in the ovarioles the nutritive cells and oöcytes become smaller until they are indistinguishable from the germ cells. The ovarioles of each ovary are joined together at the upper end by their terminal filaments, which in turn unite with those of the opposite ovary to encircle the posterior part of the ventriculus. The lower end of each ovariole opens by a very short oviduct into the common duct and vagina. The spermatheca is a round, flat pouch of light-brown color located on the dorsal side of the common oviduct, to which it is attached by a short duct along its upper circumference. It lies flat against the oviduct. The col-

leterial glands include an acid gland with its poison sac, which is connected with the base of the ovipositor by a long canal. The shorter alkaline gland narrows at its lower end to discharge alongside the opening of the acid-gland canal.

Pampel (*18*), in 1913, published a detailed account of the female reproductive organs of the ichneumonids, which he separated into four types according to their form. On the basis of the anatomical characters of these organs, *Phaeogenes nigridens* falls in his Type I, containing one member of the Joppinae and several of the Ichneumonidae (new sense).

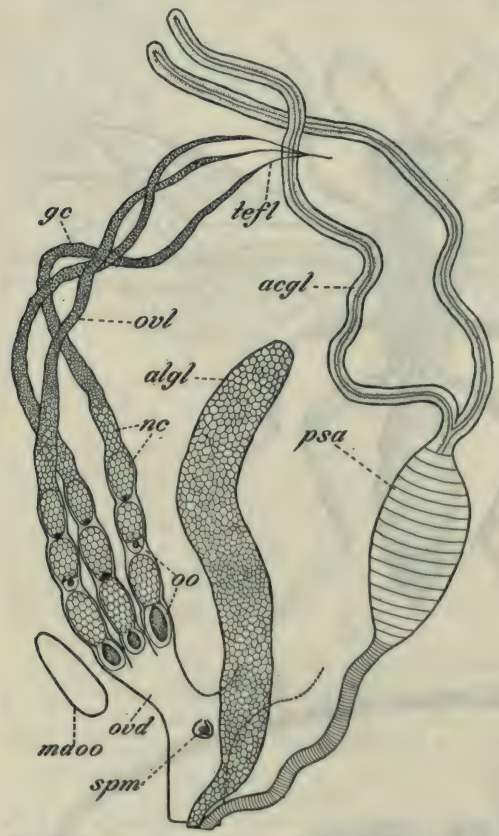


FIGURE 2.—Reproductive organs of a typical female of *Phaeogenes nigridens* 5 days old, showing the comparative size of the eggs and the associated cells and organs

EGG

Average length, 1 mm; average width, 0.29 mm.

The ovarian or newly laid egg (fig. 3, A) is hyaline, oblong-ovate, slightly arched, and entirely devoid of spines, sculpturing, or processes of any sort. It tapers gradually from the cephalic to the caudal extremity.

LARVA

PRELIMINARY REMARKS ON THE LARVAL INSTARS

It has been impossible in the case of Phaeogenes to determine exactly the number of larval instars. After dissecting a large number of the host and examining a greater number of exuviae, the writer is of the opinion that there are at least four instars, and possibly five. The data upon which this opinion is based are given below, but whatever the actual number of molted skins cast by the larva, the latter in its development assumes four distinct, easily recognizable forms. These forms will be known as primary, secondary, tertiary, and last instars.

The primary larva is easily recognized by its long, brown, heavily sclerotized head, the slender mandibles, and the absence of spiracles. The secondary larva is recognized by a protuberance of the labiobase or ventral neck region [7] of the head. The tertiary larva is recognized

[7] The ventral neck region is that part of the head skeleton between the labium and the posterior ventral border of the head.

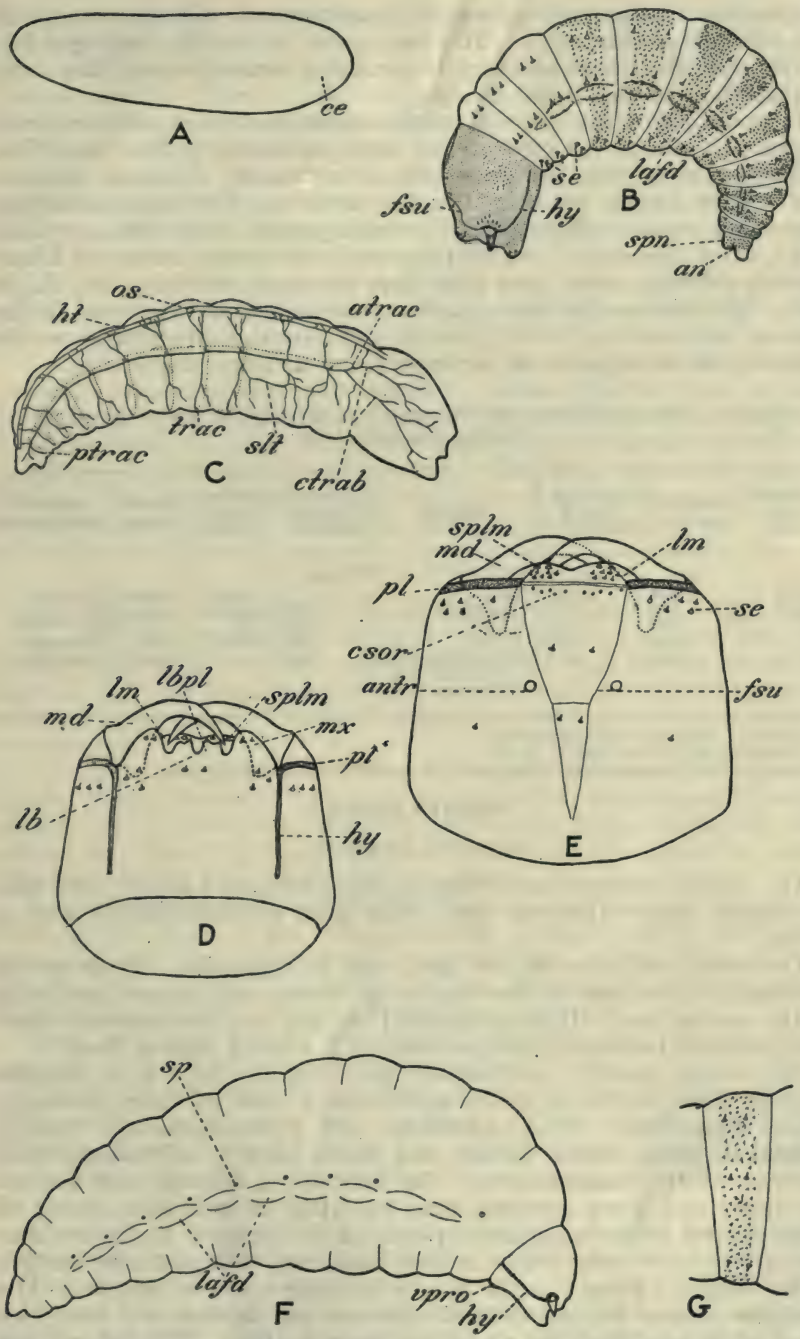


FIGURE 3.—*Phaeogenes nigridens:* A, Newly laid egg; B, unfed primary larva; C, same larva showing tracheal system and heart; D, ventral aspect of primary larval head; E, dorsal aspect of the same head; F, secondary larva; G, abdominal segment of secondary larva showing arrangement of setae and spines

by the mandibular and spiracular measurements and the absence of the ventral protuberance. The last instar is readily distinguished by its size, the mandibular and spiracular measurements, the head characters, and the dorsal hump.

It would seem from exuvial examinations that there are five larval molts. In nearly all cases three, and occasionally four and five, molted skins or pairs of mandibles were found. Absolute reliance can not be placed on these results, however, for superparasitism sometimes occurs. Sometimes Pyrausta pupae fresh from the field yield, after dissection, two or three eggs or young larvae of Phaeogenes, although never does more than one reach maturity in a single host. If there are five larval instars, they might be separated in the manner indicated in Table 1, and in this case the third instar would certainly fit in between the secondary and tertiary stages.

TABLE 1.—*Measurements and characters of the various larval forms of Phaeogenes nigridens*

Probable larval instar [1]	Length of mandible [2]	Width of base of mandible [3]	Spiracles	Diameter of thoracic spiracles	Ventral protuberance	Dorsal hump	Author's classification
	Mm	*Mm*		*Mm*			
1	0.1504	0.1080	None		Absent	Absent	Primary.
2	.1530	.1440	9, all closed	0.0090	Present	do	Secondary.
3	.1620	.1530	do	.0144	do	do	
4	.1980	.1620	do	.0198	Absent	do	Tertiary.
5	.2340	.2070	7 open during most of instar, later all 9 open.	.0469	do	Present	Last instar.

[1] Instars 1, 4, and 5 are readily determined.
[2] Measured from the lower base to the tip.
[3] Measured from the upper to the lower base of the mandible mounted on its side.

PRIMARY LARVA

EXTERNAL ANATOMY

The newly hatched larva (fig. 3, B) averages 1.25 by 0.30 mm, or slightly larger than the egg. The head averages 0.3035 mm in width.

The body, exclusive of the head, has 13 segments. When newly hatched, it is widest in the head and thorax and tapers gradually to the caudal end. It is cylindrical, white, and transparent when first hatched, becoming opaque later as the larva ingests food.

The large, heavily sclerotized head (fig. 3, D, E) is thimble shaped, light brown in color, and bears a pair of large, strongly arched mandibles. The hypostoma and pleurostoma are readily identified, being much darker and more heavily sclerotized than the rest of the head cuticle. The labrum is bilobed and has on the upper and lower surfaces, near the apex of each lobe, a pair of dome-shaped sensorial organs; posterior to these on the upper surface are 14 small setae; and farther back, near the posterior margin of the labrum, from 8 to 12 brown circular sensorial organs. The maxillae project beyond both the labrum and labium and have two small setae near the apex and three near the base. The labium has two small palpi and a pair of setae at its base. Each labial palpus has two small prolongations, the median ones bearing a short seta at the tip. The other setae on the head are located as follows:

Eight arranged in a semicircle just caudad of the pleurostoma and six widely separated on the dorsal area. The antennal rudiments are small and circular in outline and are located near the median dorsal region. The cuticle covering them is less sclerotized and more transparent than that of the rest of the head.

Dorsally from near the posterior border two faintly sclerotized sutures, probably the frontal sutures, extend forward to each pleurostoma. At the end of the instar the head splits along these sutures and back to the posterior border, thereby allowing the succeeding larva to emerge and cast its skin.

The body of the larva (fig. 3, B) has a series of lateral folds along each side extending from the second thoracic to the eighth abdominal segment, inclusive.

There are six pairs of small setae on each segment located subdorsally, laterally, and subventrally. Around the middle of each abdominal segment is a wide, compact band of minute, triangular, integumentary spines. These are apparently nonsensorial and are about one-fourth the size of the setae. The anal segment is bilobed and has two short prolongations, one inclining dorsad and the other, much shorter, ventrad. Between these is the anal opening.

Internal Anatomy

The digestive system is well developed at hatching. The fore-, mid-, and hind-intestines are easily distinguished, as are also the Malpighian tubes and salivary glands. The stomach begins in the fore part of the first thoracic segment and extends into the seventh abdominal segment. The hind-intestine is very narrow and entirely transparent.

The salivary glands arise from an almost imperceptible opening on the floor of the mouth and, branching in two near the mid-ventral portion of the head, run to the third thoracic segment on each side, where they divide into two ducts, one considerably above the other. They end in the sixth abdominal segment.

Each of the two pairs of Malpighian tubes arises from a common duct at the base of the hind-intestine in the seventh abdominal segment, and runs anteriorly along the side of the stomach and between the salivary glands to the first abdominal segment, where it turns posteriorly and stops in the next segment.

The brain and ventral nerve cord are distinct, and the latter extends to the eighth abdominal segment.

The heart (fig. 3, C) extends from the posterior border of the ninth abdominal segment into the head. It has 10 ostia, one in the middle of each segment from the second thoracic to the eighth abdominal, inclusive. It is best seen in a living specimen. There is no ostium in the ninth abdominal segment.

The tracheal system (fig. 3, C) is as follows: A main lateral trunk runs along each side of the body from the first thoracic to the ninth abdominal segment. These trunks are joined anteriorly by a dorsal transverse commissure in the first thoracic segment; from each side of this commissure run two branches to the upper regions of the head. The two larger branches, aerating the middle and lower regions of the head, arise at the point on the main trunk where it turns to cross over the stomach. Posteriorly the lateral trunks are

united by a ventral transverse commissure in the ninth abdominal segment. The lateral trunks are also united in each segment from the first to the ninth abdominal, inclusive, by a transverse ventral commissure which runs external to the nerve cord in the middle of each segment.

A secondary lateral trunk, typical of all ichneumonids thus far studied by Seurat (*24*), Thompson and Parker (*28*), and others, runs from the posterior margin of the first thoracic segment to the anterior margin of the first abdominal segment and is connected with the main trunk by three branches, one arising just caudad of the first spiracular branch, another from the anterior part of segment 2, and the third from just posterior to the second spiracular branch.

Strickland's drawing (*26, p. 13*) of the tracheal system of the second-instar larva of *Amblyteles subfuscus* Cress. does not show the secondary lateral trunk, but as a discussion of the tracheal system of the larva is not taken up in the text, further confirmation is needed before it can be classed as differing in this respect.

The main lateral trunk gives off two main branches in each segment, which in turn are much ramified. The two branches in the anal segment arise from the main trunk in the ninth abdominal segment. The secondary lateral trunk gives off branches to the lower part of the thorax and first segment of the abdomen. There are no spiracles.

SECONDARY LARVA

Length of larva near the middle of this stage, 1.91 mm; width, 0.77 mm; average width of head, 0.5816 mm.

The color and shape of the secondary larva (fig. 3, F) remain about the same as in the first instar. The head is lighter brown, less sclerotized, and much shorter. The mandibles are of approximately the same length as in the first instar, less hooked at the tip, and more robust in appearance. The other head appendages and structures, the various setae, and the sensorial organs are the same as in the previous instar. The most characteristic feature of the head is the large protuberance of the ventral neck region. The type and arrangement of setae and spines (fig. 3, G) on the body are the same as in the first instar, but the spines are not so large. The lateral folds are the same as in the first instar.

There are nine pairs of spiracles in this stage, one near the posterior border of the first thoracic segment and the remaining eight near the anterior border of the first eight abdominal segments. All are slightly dorsad of the lateral folds. In this stage they are closed and do not function.

TERTIARY LARVA

Average length, 4.80 mm; average width, 1.80 mm; average width of head, 0.83 mm.

The larva of this stage differs from that of the secondary stage by its larger size and the absence of the ventral protuberance on the head. The general characters of the head resemble more those of the last instar, except that the cuticle of the ventral neck region and base of the maxillae is much more heavily sclerotized and pigmented, the mandibles are longer and less arched on the inner side, and the spiracles are slightly larger but still closed. The setae on each segment are the same except for their smaller size. Each of the last

three abdominal segments has a wide band of minute rugosities extending around the middle of the segment. There are no spines such as are found in the primary stage.

LAST-INSTAR LARVA

EXTERNAL ANATOMY

Average length of newly molted larva, 5.90 mm; average width, 2.05 mm; average width of head, 0.96 mm; average length of fully fed larva, 10.05 mm; average width, 3.10 mm; average width of head, 1.21 mm; largest larva found, 15.50 by 3.12 mm.

The newly molted last-instar larva is cylindrical, usually light pink or tan in color owing to the material in the stomach, and opaque except in the last three abdominal segments. It is uniform in width except in the much narrower head and the last three abdominal segments, where it tapers sharply to the caudal end.

Shortly after molting a small dorsal hump begins to form in the third thoracic and first abdominal segments. (Fig. 4, A.) This gradually increases in size as the larvae grows, reaching its greatest proportions at the end of the instar. Its rigidity is preserved by the stomach, which is forced into the enlargement. The causes of this hump will be explained later under Larval Development.

The setae and rugosities on the body are the same as in the previous stage. Lateral folds are present and arranged as in the other stages. The anal segment has the same characteristic shape as in the first instar. There are nine open spiracles, but the last two do not function until the last part of the instar.

The head[8] (fig. 5), described from specimens treated with caustic potash, is transparent and composed of the usual epicranial, oral, and ventral neck regions common to hymenopterous larvae. The ventral border of the epicranium (hypostoma, pleurostoma, and epistoma)[9] is a distinctly thickened band extending from one side of the head to the other. It is brownish in color along the hypostoma and pleurostoma, but the epistoma is colorless. The clypeus is pigmented, however, and gives the impression of a continuous transverse brown band across the head, which separates the epicranium from the mouth and ventral regions. The postocciput is distinctly differentiated only near the lateral epicranial angles and at the apex; metopic suture distinct, not continuous with frontal sutures; frons triangular-shaped and lightly pigmented, frontal sutures indistinct; temporal fossae (apparently the external markings of imaginal eyes) narrow, shallow grooves; antennal rudiments large, oval, located just laterad of the frons; transverse bridge of tentorium absent, this structure probably represented by two long sclerotic spurs or apodemes extending inside the head from the lateral epicranial angles; posterior pleurostomal ramus bearing a distinct glenoid fossa in which the condyle of the mandible articulates; anterior pleurostomal ramus (superior mandibular support) reduced to a

[8] To describe the various characters of the head, the author has used well-known and accepted terms found in general entomological literature, more especially in the numerous publications of Berlese, Snodgrass, and Nelson.

[9] Thorpe (*29*), in an article on the parasites of the pine shoot moth (*Rhyacionia buoliana* Schiff.), separates several species of Ichneumonidae and Braconidae by means of the sclerotized head characters of the last-instar larva. In this paper he calls the hypostoma the mandibular strut and the combined pleurostoma and epistoma the labial strut.

slight bulge. One short sclerotic spur or apodeme extends internally from each anterior tentorial pit. This is probably the upper end of the undeveloped anterior tentorial arm or ramus. The apo-

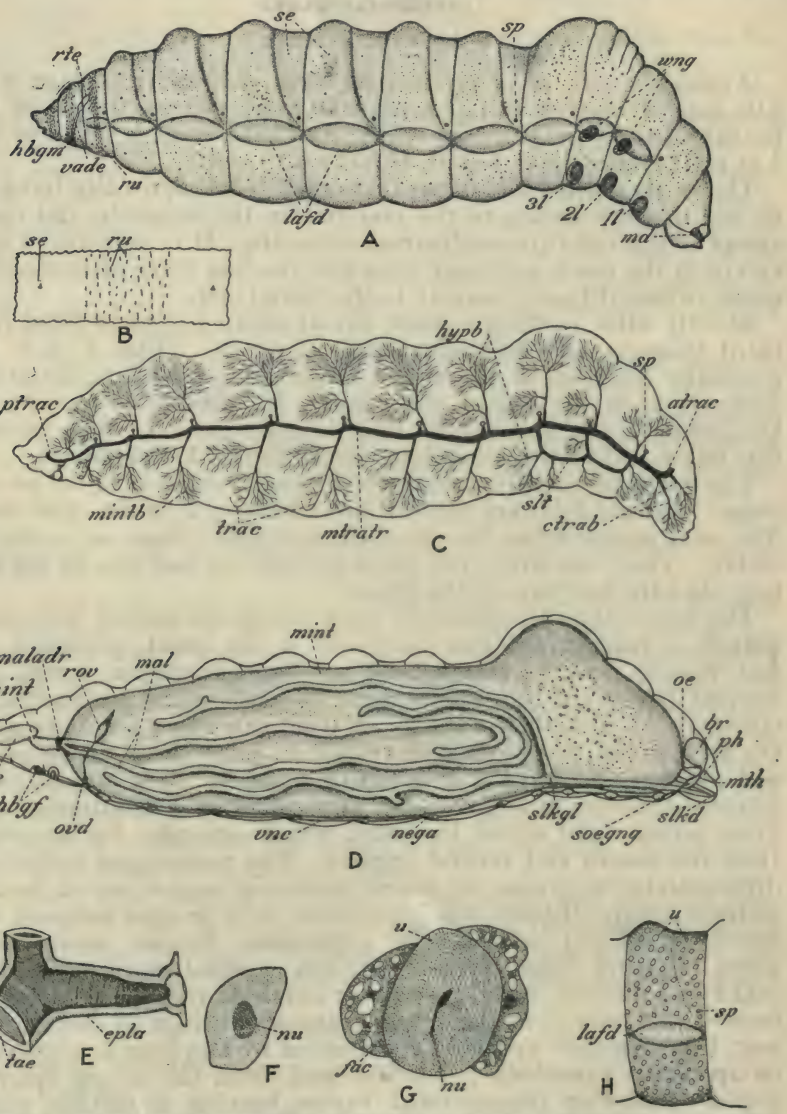


FIGURE 4.—Mature larval anatomy of *Phaeogenes nigridens:* A, Lateral aspect; B, portion of anal segment showing setae and rugosities, highly magnified; C, tracheal system; D, internal anatomy; E, spiracle of last-instar larva; F, oenocyte; G, urate cell; H, segment of abdomen showing urate cells in situ

demes extending from the anterior tentorial pits support the latero-anterior pharyngeal muscles and the apodemes of the incomplete transverse bridge of the tentorium support the ventroposterior pharyngeal muscles.

The mandibles are simple and broadly oval at base; clypeus with 4 to 6 pairs of circular sensory organs or papillae; labrum with 7 pairs of short spines arranged in 2 distinct groups, around which the cuticle is pigmented; maxillae prominent, projecting beyond the mouth and bearing 3 setae in addition to the maxillary palpus, which has 5 slightly elevated sensory organs, one of which has the form of a blunt spine; maxillary suture (the line separating the maxilla from

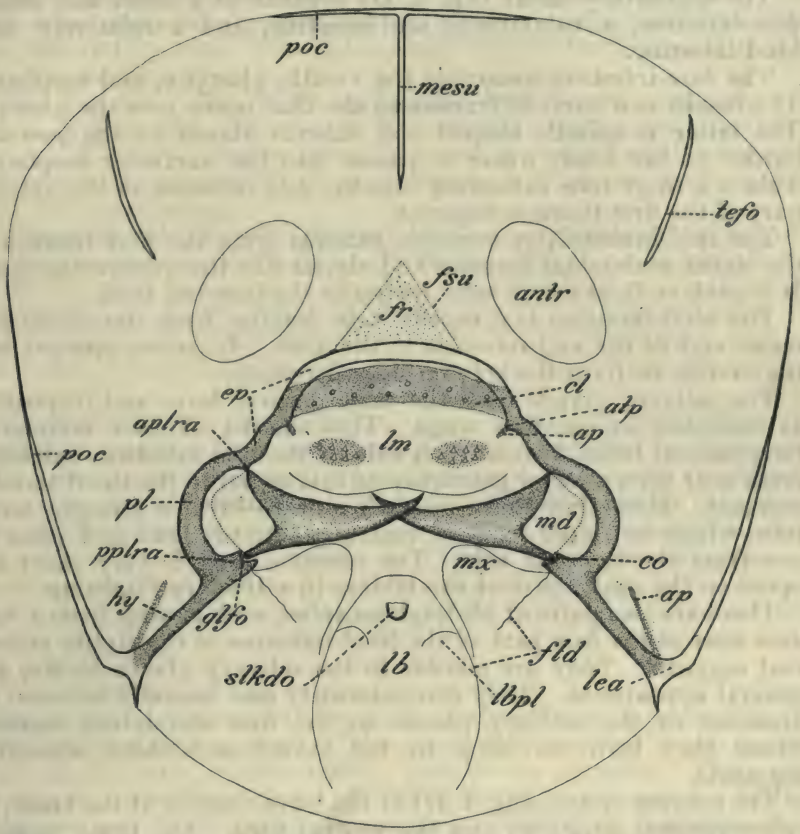


FIGURE 5.—Anatomical details of the head capsule of a mature larva of *Phaeogenes nigridens*. Stippled areas represent brown epidermal thickenings; unstippled areas (outlined by heavy lines) represent unpigmented epidermal thickenings

the ventral neck region) indistinguishable; labium distinct, bearing 3 pairs of short setae and a pair of palpi in each of which are 4 slightly elevated sensory organs, one of which has the form of a blunt spine; base of labium not sclerotized or pigmented but identified as a slight fold; ventral neck membrane or labiobase provided with 5 pairs of short setae. The U-shaped salivary-gland opening, located on the upper part of the labium, is heavily sclerotized on its sides and base. The miscellaneous setae on the epicranium are approximately the same in arrangement and number as those of the first instar.

The principal characters of the mature larval head of *Phaeogenes nigridens* may be summarized as follows: The heavily sclerotized

ventral epicranial border, the absence of the tentorial bridge, and the indistinct sutures of the maxillary and labial regions. When the larvae of this group have been more extensively studied, it will be interesting to see whether or not these characters will be found generally applicable to the Joppinae.

Internal Anatomy

The alimentary canal (fig. 4, D) consists of a short and slender fore-intestine, a voluminous mid-intestine, and a relatively short hind-intestine.

The fore-intestine comprises the mouth, pharynx, and esophagus. The mouth is a narrow, transverse slit that opens into the pharynx. The latter is spindle shaped and extends almost to the posterior border of the head, where it passes into the narrower esophagus. This is a short tube extending into the mid-intestine in the anterior part of the first thoracic segment.

The mid-intestine, or stomach, extends from the first thoracic to the eighth abdominal segment and almost fills the intervening space. It is pink or light tan in color owing to the ingested food.

The hind-intestine is a narrow tube leading from the closed posterior end of the mid-intestine to the anus. It curves upward near the middle to form the spindle-shaped rectum.

The salivary glands have the same general form and disposition as described in the first stage. They consist of four undulating longitudinal tubes, two on each side of the mid-intestine, extending from near the posterior extremity of this organ to the third thoracic segment. Here they unite on each side to form a straight single tube, which continues forward ventrally into the head and joins the one from the opposite side. The common duct is very short and opens on the upper part of the labium in a U-shaped opening.

There are two pairs of Malpighian tubes, each arising from a common duct at the fore part of the hind-intestine in the eighth abdominal segment. They are similar to the salivary glands in size and general appearance. They run anteriorly and laterally between the branches of the salivary glands to the first abdominal segment, where they turn and stop in the second and third abdominal segments.

The nervous system (fig. 4, D) of the larva consists of the brain, the subesophageal ganglion, and the ventral cord. The brain occupies the upper part of the head and extends slightly into the thorax. It is connected to the succeeding ganglia by two cords which encircle the middle portion of the pharynx. The subesophageal ganglia are elongated and fused. They are located just below the pharynx in the posterior part of the head.

The ventral nerve chain includes 11 double ganglia, the terminal one being in the seventh abdominal segment. The thoracic and terminal ganglia are the largest except those in the head. The first abdominal segment has two ganglia, and the others have one in each. The ganglia give off nerves which control the various muscles, sensory organs, and histoblasts of the locomotive and reproductive organs.

The nerves in the thorax and the first abdominal segment arise from the ganglia in the same segment, whereas those in the other

segments originate from ganglia in the preceding segment. The terminal ganglion (fig. 6, F) is evidently a fusion of the ganglia of the last three segments, as it sends out three pairs of nerves, one pair for each segment.

The tracheal system (fig. 4, C) is essentially the same as in the preceding instars, but the branches are much larger and more ramified. Two pairs of branches extend from the anterior transverse commissure to the upper and lower regions of the head. The first seven spiracles function during the entire stage, but the eighth and the ninth are not open to the exterior until the larva has nearly finished feeding.

The oenocytes (fig. 4, F) are visible only in sectioned material, where they are very conspicuous on account of their great affinity for stains. They are usually found in small groups of contiguous cells along the laterad portion of the abdomen. They are much smaller than the urate cells.

The urate cells (fig. 4, G, H) are white and irregularly shaped and easily seen through the body of the larva. They are found only between the first and ninth abdominal segments and are arranged in 4 large longitudinal groups, 2 subdorsally and 2 subventrally. In sections they are usually found closely surrounded by slightly smaller fat cells. The cytoplasm of the urate cells has slight affinity for stains.

The histoblasts or imaginal buds (fig. 4, A, D; fig. 6, A, F) of the various external organs are most easily distinguished in this stage. The most conspicuous ones are the antennal histoblasts situated in the antennal rudiments, the wing buds found laterally in the second and third thoracic segments, the leg buds located ventrally on each segment of the thorax, and the histoblasts of the genitalia located ventrally in the eighth and ninth abdominal segments in the female and in the ninth abdominal segment in the male. All the histoblasts of the external organs, being semiopaque and lying just underneath the cuticle, are very easily distinguished.

The rudiments of the ovaries (fig. 4, D; fig. 6, F) consist of two spindle-shaped bodies with long, narrow stalks, both located in the seventh abdominal segment. The ovaries are attached to the ventral wall of the heart in the anterior part of the segment. Their oviducts run posteriorly under the ventrolongitudinal muscles to two points on the integument in the posterior part of the segment.

The rudiments of the testes (fig. 4, A) are found in the eighth and ninth abdominal segments. They are peanut shaped and lie above the union of the hind-intestine and mid-intestine. Each has a short, narrow stalk with a deep slanting constriction just before it enters the histoblast of the genitalia.

The imaginal buds or rudiments of the Malpighian tubes (fig. 4, D) become very prominent at the end of this stage. They arise from the anterior end of the hind-intestine just back of the larval Malpighian tubes.

Muscular System

The muscles of the head (fig. 6, B) can be divided into five groups, according to their location and function. The first and most powerful group is that operating the mandibles, comprising the extensor

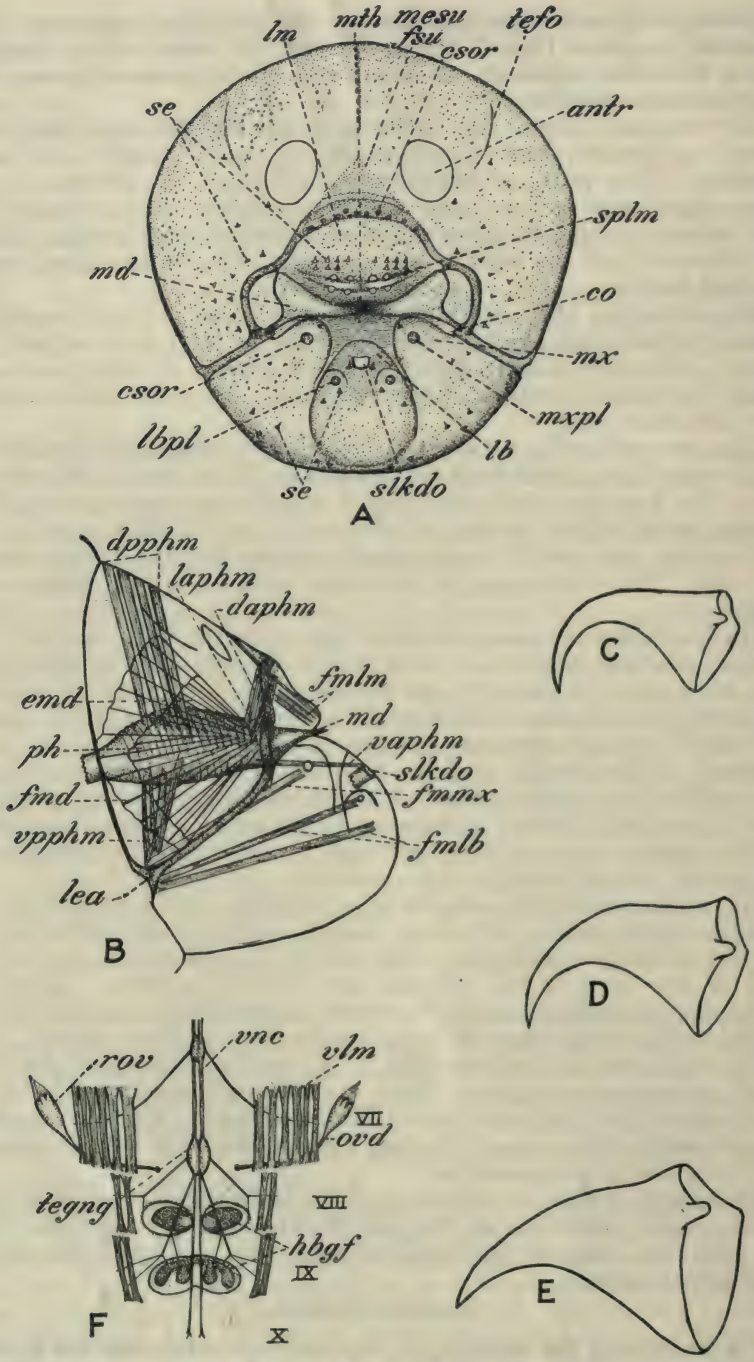


FIGURE 6.—Anatomical details of *Phacogenes nigridens* larva: A, Anterior aspect of mature larval head; B, lateral aspect of mature larval head, showing muscular system; C, D, and E, mandibles of primary, secondary, and last-stage larvae; F, rudiments of female reproductive organs viewed from inside the mature larva. VII, VIII, IX, and X refer to respective abdominal segments

and flexor muscles. The flexor muscle is twice as large as the extensor and occupies more than one-half the width of the head. The second group is that of the pharynx, from which arise five pairs of muscles varying greatly in size. Two muscles of four strands each run from the upper posterior part of the pharynx to the dorsal part of the head directly above. Two more muscles of four strands each extend from the lower posterior part of the pharynx to the two sclerotic spurs or apodemes projecting inward on each side of the head from the bifurcations of the hypostoma. The fore part of the pharynx has three pairs of smaller muscles, two pairs running from the upper part to the epicranial suture supporting the labrum and a very light pair running from the lower surface to the salivary-duct opening. The third group, operating the labrum, is composed of

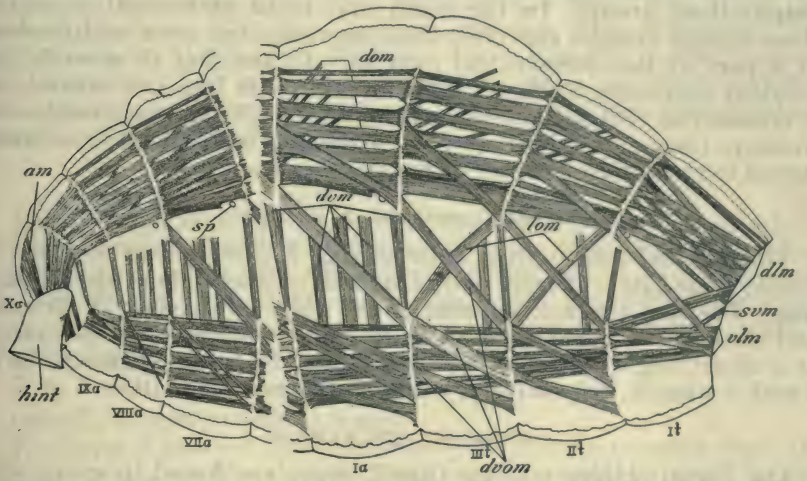


FIGURE 7.—Integumentary muscles of mature *Phaeogenes nigridens* larva (left side) located in the three thoracic (*t*) and the first, seventh, eighth, ninth, and tenth abdominal (*a*) segments. Roman numerals refer to segments

two pairs of narrow muscles, the medial pair having one strand and the other having two strands each. The medial pair runs from the area between the antennae to the extreme anterior part of the labrum. The other pair runs from just anterior to the epicranial suture to the mouth opening. The fourth group is composed of one pair of muscles of one strand each and extends from just dorsad of each apodeme to the maxillae. The fifth group has one pair of two strands each, which extend from just ventrad of each apodeme to the labium.

The muscles of the thorax and abdomen (fig. 7) have a more or less uniform arrangement throughout and can be separated into a series of distinct groups, as was the case with those of the head.

VENTRAL LONGITUDINAL MUSCLES

The ventral longitudinal muscles (fig. 7, *vlm*) consist of from 4 to 6 strands in each segment except the last abdominal, where there are only 2, running from the posterior border of the ninth abdominal segment to the anal opening.

DORSOVENTRAL OBLIQUE MUSCLES

The dorsoventral oblique muscles (fig. 7, *dvom*) overlie all the other integumentary muscles and extend anteriorly in a dorsoventral direction. Between the head and the fourth abdominal segment the muscles begin at the posterior line of attachment of the dorsal longitudinal muscles in each segment, and cross four segments to end just ventrad of the ventral longitudinal muscles. Each of these muscles is attached to the hypodermis where it crosses the intersegmentary line. In the first and second thoracic segments one muscle extends from the middle posterior portion of the dorsal longitudinal group to the head at the middle of the ventral longitudinal muscles. In the fourth to seventh abdominal segments, inclusive, the oblique muscles cross only three segments, originating just laterad of the dorsal longitudinal group. In the ninth and tenth abdominal segments these oblique muscles also cross three segments, but are a continuation of a part of the dorsoventral muscles. In the first to seventh abdominal segments, inclusive, each muscle splits into two strands as it crosses the ventral longitudinal muscles. The upper strand continues to the anterior border of the preceding segment and the lower strand to the anterior border of the same segment.

DORSAL LONGITUDINAL MUSCLES

These dorsal longitudinal muscles (fig. 7, *dlm*) comprise a set of mostly wide bands of from 5 to 11 strands on each side of the median line. The first thoracic segment is the only one having 11 strands, and these are in 2 groups, 1 above the other and crossing each other at a slight angle. The sixth and seventh abdominal segments have 6 and 5 strands, respectively, while the others have either 6 or 7.

DORSAL OBLIQUE MUSCLES

The dorsal oblique muscles (fig. 7, *dom*) are found in every segment but the first and last two. They vary from three slender bands in the second segment to eight in the seventh abdominal on each side. Their number varies with different individuals. Their posterior ends are attached to the posterior margin of each segment, and they run slightly dorsad to attach themselves near the middle of each segment. They lie exterior to the dorsal longitudinal muscles. All are in a compact parallel series, except one which runs to just posterior to the spiracle in the first to seventh abdominal segments, inclusive.

DORSOVENTRAL MUSCLES

In each segment but the first thoracic and last two abdominal segments there are from 1 to 3 muscles (fig. 7, *dvm*) on each side, which extend from ventrad of the lowest dorsal longitudinal muscle to underneath the upper strand of the ventral longitudinal muscles. The second and third thoracic segments have 1 muscle each, near the anterior border. Each of the first eight segments of the abdomen has three placed evenly throughout. Besides the muscles in the segments there is 1 strand which is located along each intersegmental line, making 12 in all. This muscle has its attachment and direction similar to the others.

MISCELLANEOUS MUSCLES

In the first segment there is one small subventral muscle (fig. 7, *svm*) running from the head on each side to a point midway in the segment. The second and third thoracic segments have two lateral oblique muscles (fig. 7, *lom*) running cephalad from a point just under the upper ventral longitudinal muscle at its posterior attachment to a point near the attachment of the lower dorsal longitudinal muscle. In the anal segment there are four light bands (fig. 7, *am*) running from near the posterior end of the heart to the anal opening.

The most powerful muscles of the trunk are the ones in the dorsal longitudinal group, and especially those in the thorax, where they are brought into frequent action by the constant bending of this part of the body to permit the larva to secure the food lying along the wall of the host. The dorsal oblique muscles, when contracted, are responsible for the deep constrictions found dorsally in their respective segments. The muscles of the eighth, ninth, and tenth abdominal segments are much thinner and weaker than the corresponding muscles of the other segments.

PREPUPA

The prepupa is of the usual hymenopterous type. It is of about the same length as and more slender than the mature larva and has a constriction in the first abdominal segment. Most of the appendages of the adult head appear in the larval head; the eyes show up in the first thoracic segment, and the stomach now completely fills the caudal end.

PUPA

Length, 10 mm; width, 2.5 mm.

The pupa is inclosed in a thin, closely fitting, transparent case. It almost completely fills the host pupa and is usually oriented in the same direction as the host.

There is a loose network of silk attached to the inside of the host pupa, but it can hardly be called a cocoon.

BIOLOGY

EMERGENCE

When ready to emerge, the adult splits its pupal skin at the head end and by its contortions slowly works it off the body in one piece. Just before this skin leaves the abdomen, that part of the adult meconium inclosed in a peritrophic membrane is discharged. This is an oval-shaped sac 1 by 2.5 mm closed at one end and containing a white granular substance. The adult then goes through a resting period of about 24 hours, during which the wings and other organs become adjusted to the changed conditions. Also during this time more white meconial matter is cast in a soft mass, but devoid of any peritrophic membrane. Finally the adult chews an irregularly shaped hole near the head of the host and pushes itself out.

In only one instance has the writer observed an emergence hole in the caudal end of a host pupa. Often the opening is made so large

that the host head is broken off when the adult emerges. The hole is usually made on the ventral side.

Emergence takes place at any time during the day or night, in this respect differing from that of *Theronia atalantae* Poda, a rare pupal parasite of *P. nubilalis*, which, according to Constantineanu (*9*, *p. 423*), emerges only during the night.

BEHAVIOR ON THE FIRST DAY AFTER EMERGENCE

During the first 24 hours after emergence the adult remains in a lethargic condition and moves about only when disturbed. The abdomen in the early part of this period contains numerous large white cells closely resembling the urate cells of the larva, and within the first few hours these disappear coincidently with evacuation of the remaining meconium. This meconium is often in the shape of small white pellets. Whether the disappearance of the white bodies in the abdomen has any direct relation to the discharged meconium it was impossible to determine, but the writer believes that these groups of cells are eliminated by way of the hind-intestine or Malpighian tubes.

In all cases where adults died within two or three days after emergence it was noted, by external view as well as by dissection, that these cells were still intact. The average time required for the complete discharge of the meconium was three hours. Adults which showed none of these cells on the second day always had normal longevity.

Mating was not usually attempted before this adult meconium was cast. Temperatures below 10° C. (50° F.) were often fatal to adults that had not completed this evacuation.

LIGHT REACTION

Immediately after emergence both sexes appear positively phototropic to a slight degree. After a few hours the female loses this reaction, and during the remainder of her life exhibits only a strong negative phototropism. The male retains the positive phototropic reaction, although it is somewhat diminished later in life. This tendency of the female to conceal herself in a dark corner adds difficulties to the handling in laboratory breeding work. When the female is suddenly exposed to an ordinary electric light, she will fly directly into it and flutter there for several minutes before becoming adjusted to her surroundings and seeking the dark.

FOOD

Both sexes feed readily on honey, raisins, and other fruits, but the best results in survival were obtained by feeding the adults sugar solution. Dry sugars attract the adults only slightly. The parasite does not normally take any nourishment from the host. Only in one instance, when the host was broken and exuding part of its blood, did the writer notice a female feeding from this source. This is somewhat different from the feeding of another pupal parasite of the borer, *Itoplectis ephippium* Brullé, which punctures the fresh white pupae and greedily laps up the blood, often causing the death of the host.

MATING

Mating may take place, as to both sexes, within a few hours after emergence. Apparently one mating is sufficient for the proper fertilization of the eggs, and one male is able to fertilize many females. The male parasite will not mate before voiding the meconium, but the female will permit mating prior to such voidance. For breeding purposes, however, it is deemed advisable to isolate the female until the end of this period, as otherwise some die shortly after mating. The female attracts the male whether or not she has already been fertilized, but if this has taken place the male usually turns away after a quick examination with his antennae. The average length of time spent in mating is one minute.

Mating can be secured under a great variety of conditions, but the writer's best results have been obtained by placing a male 1 or more weeks old in a 2-mm vial with a female less than 1 day old and forcing them by means of the cotton plug to occupy as small a space as possible.

Mating will take place at any temperature between 18° and 30° C. (64.4° and 86° F.), but the preferred range is from 20° to 25° C. (68° to 77° F.). A female more than a week old is very difficult to mate, the males being only mildly attracted to her, if at all; but when some of the larval meconium and cast skins in the old host pupa were brushed lightly over her body with a fine camel's-hair brush, mating took place immediately. It would seem, therefore, that the odor of this material plays an important rôle in inducing mating.

These details of mating have importance in connection with the artificial or controlled breeding of the parasite.

OÖGENESIS

At emergence there is usually only one extremely miniature egg at the base of each follicle. Females fed on sugar solution and kept at 25° C. (77° F.) developed their first mature eggs in from one to two weeks, the average being 11 days. At the end of this period there were from 1 to 6 fully developed eggs and from 9 to 12 partly developed ones. At the end of three weeks there were from 6 to 12 fully developed eggs, and if none was laid the lowest ones disintegrated and passed out through the oviduct. No eggs were ever found in the oviduct—a strong contrast with the condition obtaining in many other ichneumonids and braconids. Table 2 shows the development of the ovarian eggs of various females when exposed to different temperatures. The females used in the experiment were held more or less closely at their respective temperatures, being kept only for a half hour twice a week at room temperature to permit better feeding conditions.

TABLE 2.—*Approximate time required to develop mature eggs in the ovaries of females of Phaeogenes nigridens exposed to different temperatures*

Number of individuals	Temperature of cage		Time required to develop mature eggs	Number of individuals	Temperature of cage		Time required to develop mature eggs
	°C.	°F.			°C.	°F.	
10	25	77.0	11 days.	4	8	46.4	7 weeks.
3	18	64.4	4 weeks.	5	5	41.0	12 weeks.

OVIPOSITION

The female prefers freshly formed white or light-brown pupae in which to oviposit, seldom paying any attention to pupae that are more than 2 days old. This may be due to the difficulty of piercing the hard pupal shell. She will oviposit in pupae lying loose or concealed in artificial or natural tunnels, but prefers those lying in their cocoons, the restricted space therein appearing to aid her in ovipositing.

Oviposition takes place at any temperature between 18° and 30° C. (64.4° and 86° F.), with a slight preference for temperature midway between these extremes.

When supplied with a pupa in a cornstalk tunnel, the female is first attracted to the tunnel itself. She enters this, feeling with her antennae as she goes, until she reaches the host cocoon. After examining this slightly, she forces an opening in it by cutting some of the silk with her mandibles. If she finds that the host is newly pupated, she quickly crawls inside with her head near that of the host, grips the struggling pupa with her legs, arches her abdomen, and thrusts in her ovipositor. Perforation of the pupa is usually made at the base of the wing pads or in its proximity. The entire length of the ovipositor is pushed inside and held there from 30 to 60 seconds. Occasionally she moves this organ up and down slowly in the host before depositing the eggs. Only one egg is deposited at a time, and ordinarily only one is deposited in a given host.

While the ovipositor remains inside, the pupa usually ceases its movements but resumes them as soon as the ovipositor is withdrawn, often continuing them for several minutes after the parasite has left. This struggling, instead of discouraging the female, seems to accentuate her desire to oviposit.

When a brown pupa—viz, one 3 days or more old—is encountered in the corn-borer tunnel, the female usually leaves without entering the cocoon. If she does enter and attempt oviposition, her efforts are often unsuccessful owing to her inability to pierce the hard sclerotic case during the violent struggles of the host. When she is successful, it is usually because the ovipositor has struck the softer part located between the telescoping segments.

The hole made by the ovipositor in the host integument usually permits some of the host blood to exude, which seals the opening. When dry, this blood turns black and leaves a characteristic spot by which parasitized pupae can be recognized in many instances.

In the field, as well as in the laboratory breeding, more than one egg is occasionally found in a host. Where two are placed in the same host, one of the resulting larvae kills the other with its long hooked mandibles as soon as they come in contact, usually in the first stage.

Occasionally the writer has seen a female thrust her ovipositor into the host without depositing an egg. It is possible that, although stimulated to oviposit by the presence of the host, she has not an egg sufficiently developed for deposition, especially as her ovaries can hold but very few mature eggs, three being the average and six the maximum found in a laying female. One female, dissected after she had punctured the host in this manner, contained no developed eggs.

When given loose pupae, the female shows a keen interest in the cast-off skin of the larva, especially the head capsule, and examines this very carefully before hunting for the pupa. Corrugated paper strips which contain or have contained pupae always excite her, and even corrugated paper which has never been exposed to Pyrausta larvae arouses her interest. She is apparently attracted by its rough surface, as smooth paper does not produce the same reaction.

Females are most active in the sunlight or at high temperature. When exposed to direct sunlight, they become more active under its influence, but they soon move away to a shady place. Semidarkness appears to stimulate oviposition to its greatest extent.

Females are never interested in Pyrausta larvae or prepupae.

In the laboratory breeding experiments three has been the maximum number of eggs laid in any one day, showing that the female has a prolonged oviposition period.

Pupae of *Sesamia* (*nigraiaes vuteria* Stoll, a pest of corn in ales, but in these of Lepidoptera habits and a life

Technical Bulletin No. 331,
United States Department of
Agriculture.

Page 25, line 16, for
"Sesamia (nigraiaes vuteria
Stoll," read "Sesamia (nigroides)
vuteria Stoll."

of the pupa, but dy to hatch, the l of a binocular s is the case with ıds to the caudal terior portion of es the large head ich is then easily e larva emerges. moved or eaten are eggshells of *Euimneria crassifemur* Thom., *Campoplex multicinctus* Grav.,[10] and *C. pyraustae* Smith,[10] also parasitic on the borer.

The incubation period at 25° C. (77° F.) was approximately two days and at 18° C. (64.4° F.) about twice as long. This was determined by dissecting the host near the end of each period, when practically all the eggs were found to contain fully developed larvae. The eggs were then placed in normal salt solution, and the larvae emerged a few hours later.

Tothill (*31, p. 95*), in describing *Therion morio* Fab., an ophionine parasite attacking the larva and emerging from the pupa of the fall webworm (*Hyphantria cunea* Drury), states that "an unattached egg in a pupa undergoing histolysis would be at a disadvantage in the matters of oxygenation and phagocytic attack compared with an egg attached to the inner side of the wall of the pupa." He also states that the phagocytic action taking place in the pupa during formation of the adult organs is fatal to unprotected eggs or larvae of parasites attacking this stage of the host. The writer can not agree with these statements, as his study of Phaeogenes has shown

[10] From unpublished notes of the writer.

OVIPOSITION

The female prefers freshly formed white or light-brown pupae in which to oviposit, seldom paying any attention to pupae that are more than 2 days old. This may be due to the difficulty of piercing the hard pupal shell. She will oviposit in pupae lying loose or concealed in artificial or natural tunnels, but prefers those lying in their cocoons, the restricted space therein appearing to aid her in ovipositing.

Oviposition takes place at any temperature between 18° and 30° C. (64.4° and 86° F.), with a slight preference for temperature midway between these extremes.

When supplied with a pupa in a cornstalk tunnel, the female is first attracted to the tunnel itself. She enters this, feeling with her antennae as she goes, until she reaches the host cocoon. After examining this slightly, she forces an opening in it by cutting some of the silk with her mandibles. If she finds that the host is newly pupated, she quick
host, grips the stru
and thrusts in her
made at the base o
length of the ovipo
60 seconds. Occasi
in the host before d
a time, and ordinar
While the ovipo
movements but resu
often continuing th
This struggling, in
tuate her desire to
When a brown p
in the corn-borer t
the cocoon. If she
are often unsuccess
sclerotic case during the violent struggles of the host. When she is successful, it is usually because the ovipositor has struck the softer part located between the telescoping segments.

The hole made by the ovipositor in the host integument usually permits some of the host blood to exude, which seals the opening. When dry, this blood turns black and leaves a characteristic spot by which parasitized pupae can be recognized in many instances.

In the field, as well as in the laboratory breeding, more than one egg is occasionally found in a host. Where two are placed in the same host, one of the resulting larvae kills the other with its long hooked mandibles as soon as they come in contact, usually in the first stage.

Occasionally the writer has seen a female thrust her ovipositor into the host without depositing an egg. It is possible that, although stimulated to oviposit by the presence of the host, she has not an egg sufficiently developed for deposition, especially as her ovaries can hold but very few mature eggs, three being the average and six the maximum found in a laying female. One female, dissected after she had punctured the host in this manner, contained no developed eggs.

When given loose pupae, the female shows a keen interest in the cast-off skin of the larva, especially the head capsule, and examines this very carefully before hunting for the pupa. Corrugated paper strips which contain or have contained pupae always excite her, and even corrugated paper which has never been exposed to Pyrausta larvae arouses her interest. She is apparently attracted by its rough surface, as smooth paper does not produce the same reaction.

Females are most active in the sunlight or at high temperature. When exposed to direct sunlight, they become more active under its influence, but they soon move away to a shady place. Semidarkness appears to stimulate oviposition to its greatest extent.

Females are never interested in Pyrausta larvae or prepupae.

In the laboratory breeding experiments three has been the maximum number of eggs laid in any one day, showing that the female has a prolonged oviposition period.

Pupae of *Sesamia* (*nigraiaes vuteria* Stoll, a pest of corn in southwestern France, were exposed to different females, but in these they showed no interest whatever. This species of Lepidoptera occurs in company with Pyrausta in corn and has habits and a life somewhat similar to it.

INCUBATION

The egg of Phaeogenes floats freely in the body of the pupa, but it is always found where laid. In eggs nearly ready to hatch, the forming larva may easily be detected with the aid of a binocular microscope. The abdomen is not folded on itself, as is the case with many ichneumonid larvae, but is straight and extends to the caudal extremity of the egg. As it completely fills the posterior portion of the egg, a slight movement of the inclosed larva causes the large head to come into close contact with the cephalic end, which is then easily broken open by the long, sharp mandibles, and the larva emerges. The eggshell remains where the egg was laid unless moved or eaten by the larva and is never attacked by phagocytes as are eggshells of *Eulimneria crassifemur* Thom., *Campoplex multicinctus* Grav.,[10] and *C. pyraustae* Smith,[10] also parasitic on the borer.

The incubation period at 25° C. (77° F.) was approximately two days and at 18° C. (64.4° F.) about twice as long. This was determined by dissecting the host near the end of each period, when practically all the eggs were found to contain fully developed larvae. The eggs were then placed in normal salt solution, and the larvae emerged a few hours later.

Tothill (*31, p. 95*), in describing *Therion morio* Fab., an ophionine parasite attacking the larva and emerging from the pupa of the fall webworm (*Hyphantria cunea* Drury), states that "an unattached egg in a pupa undergoing histolysis would be at a disadvantage in the matters of oxygenation and phagocytic attack compared with an egg attached to the inner side of the wall of the pupa." He also states that the phagocytic action taking place in the pupa during formation of the adult organs is fatal to unprotected eggs or larvae of parasites attacking this stage of the host. The writer can not agree with these statements, as his study of Phaeogenes has shown

[10] From unpublished notes of the writer.

that neither eggs nor larvae have ever been found dead from any cause originating from the host.

Cushman (*10*) treats of various types of parasitism among the Ichneumonidae, with particular reference to the egg, larval form, and habits. *P. nigridens*, on account of its habits and more especially its larval anatomy, appears to fit into Cushman's second type of internal parasites along with *Amblyteles vadatorius* Illiger and *Ichneumon sarcitorius* L. and probably others of the subfamily Joppinae. Both of the last two species, however, lay their eggs in the last-stage larvae, and the adults emerge from the pupae of the lepidopterous host, whereas Phaeogenes passes its entire life cycle in the pupa. The egg is identical with that of *I. sarcitorius*, according to the drawing of Chewyrev (*8*). The general form of the Phaeogenes first-stage larva is also very similar to Chewyrev's drawings of the same stage of *I. sarcitorius* and *A. vadatorius*, particularly in respect to the head. On the basis of the appearance of the egg and the characters of the first-stage larva, Phaeogenes is more closely allied with this group than with any of the others.

LARVAL DEVELOPMENT

FEEDING

The generally accepted theory on the feeding habits of internal parasitic larvae is that advanced by Ratzeburg (*21*, *p. 13*). He believed that such larvae feed upon the lymph and blood of the host rather than on the solid tissues. Later Timberlake (*30*, *p. 88*), as a result of his study of *Limnerium validium* Cress., contended that the small larvae of this species "institute pathological changes" which break down the solid tissues to a size which can be readily swallowed by the larva. The last-stage larva, having in addition "chitinized, supporting, or possibly rasping ridges" around the mouth, was believed to be able to ingest solid tissues even before they had been entirely disintegrated.

With Phaeogenes, however, the writer believes that the larva, no matter in what instar, always breaks down the large fat bodies, chiefly by its mandibles. In the first stage particularly the mandibles seem to be larger in comparison with the size of the head.

The writer has noticed in dissections that, when a first or second instar larva is encountered in the host, the fat bodies are always broken up into small pieces, whereas a normal host has its fat distributed in comparatively large masses. When the last instar is reached, there is very little liquid food left, and thus the larva has to depend on the solid matter. Most of these older larvae, when dissected, have parts of some host organ projecting from the mouth.

During the process of feeding, the labrum, the maxillae, and to a lesser extent the labium are continually pushed in and out while the mandibles tear and direct the food into the mouth.

The food of the first and second instar larvae is mainly the blood and fat of the host. In the third stage, however, the larva attacks the vital organs and some of the integumentary muscles—in fact, almost everything except the large tracheal branches.

GROWTH

With *P. nigridens*, as with many parasites whose larvae live internally, it was difficult to follow the larval development closely. However, by completing numerous dissections and making a study of the various body, head, and mandibular measurements and the number of molted skins, a fairly accurate estimation of the larval development was obtained.

At various intervals dissections were made of parasitized pupae reared at a constant temperature of 25° C. (77° F.), and the results showed the length of each larval stage to be approximately as follows:

	Days
Primary stage	1
Secondary stage	1¼
Tertiary stage	1
Last stage	2¾
Total	6

These figures are somewhat low for the actual larval period under field conditions in the spring, as the mean temperature at this time is from 16° to 20° C. (60.8° to 68° F.), depending on the zones. In the second generation, however, which develops during the latter part of July and the first part of August in the 2-generation host zones, the larval development follows very closely the above rates, and the parasite has in normal years a total larval period of from 6 to 10 days.

No notes were made on the length of the larval stages at 18° C. (64.4° F.), but as the total time from egg to adult at 25° C. (77° F.) was just one-half what it was at 18° C., it may not be far wrong to estimate each instar on this basis. This would give for the entire larval stage a period of about 15 days. At constant temperatures below 14° C. (57.2° F.) the larvae did not seem to develop well, and most of them died without pupating.

ACTIVITY IN THE HOST

The activity of the larva within the host could be followed only within certain limits. Hence, the data were obtained by making a large number of dissections and noting the position, food, etc., of the larva found therein.

After hatching from the egg, the larva makes its way, feeding as it goes, toward the posterior end of the abdomen, where it remains throughout the short first and second stages. Its activity during these two stages is much greater than during the last instar, but in all its migrations it rarely enters the anterior half of the host. It moves about by bending and straightening out its body, the numerous spines and finlike shape of its caudal extremity aiding it in these movements.

During the early part of the last instar the larva is almost as active as in the previous instar; but as it becomes larger and its width approaches that of the host pupa it takes a permanent position with its head facing the anterior end of the host. It now almost fills the posterior half of the pupa. At this point the development of the

dorsal hump begins. This is a gradual process, and the hump attains its largest proportions at the end of the stage. A possible explanation of the cause of this character is as follows:

As most of the food lying in the middle of the host has already been devoured, the larva has to feed on those tissues clinging to the body wall. To do this in such close quarters, the width of the larva being practically the same as that of the host, requires the thorax to be bent at a right angle with the body, thus forcing the dorsal part of the third thoracic and first abdominal segments to bulge out into the open space in front. This characteristic larval hump has never, to the writer's knowledge, been recorded as occurring in any other ichneumonid.

As the larva grows, it pushes against the posterior end of the pupa, causing the abdomen to extend. The undevoured muscles controlling this region of the host body have already been rendered functionless by the destruction of the nervous system; so the segments are no longer able to retract, therefore remaining in this position permanently. If the pupa is disturbed at this time, the imprisoned larva moves its body and the host abdomen is moved along with it. Hitherto the activity of the host has remained entirely unaffected by any movements of the larva. When completely fed, the larva fills all that part of the host posterior to the head and first two thoracic segments.

Many species of ichneumon larvae which pupate within the pupae of their hosts spin a thin film of silk across the inside of the host's head, as with *Ichneumon rubens* Fons. (*3*, *v. 63*, *p. 258*), or around themselves, as with *Amblyteles subfuscus* Cress. (*26*). *Itoplectis conquisitor* (Say), according to Fiske (*12*, *p. 196*), often spins a little brownish silk "over the interior surface of the pupa shell. Any accidental opening if not too large in the anterior portion will be repaired by a thin membrane of this substance." The larva of *Phaeogenes nigridens* is similar to the last species in this respect.

PREPUPAL DEVELOPMENT

Intervening between the larval and pupal stages there is a short period during which the parasite prepares itself for transformation into the pupa. Although this may not represent a true instar as judged by ecdysis, it is so entirely different from any other instar that it can be considered as a distinct stage of ontogenesis.

To determine the prepupal period, records were made of eight parasitized Pyrausta pupae kept constantly at 25° C. (77° F.), and these showed the average length of the prepupal stage to be one and one-half days. At 18° C. (64.4° F.) it was correspondingly longer.

In an effort to determine this period more accurately, many fully fed larvae were removed from the host, but all died without completing this stage. In addition, a number of host pupae were opened slightly in order to see the mature larva or prepupa within, but the parasite so treated rarely reached the pupal stage.

The exact starting point of the prepupal stage is always difficult to fix, but the writer has arbitrarily placed it as the time when the

eyes first appear as small reddish spots. At about the same time the larval organs in the head break down and make way for the adult mouth parts and antennae, the dorsal hump disappears, and the larva becomes slightly longer and narrower. The adult head forms in the first thoracic segment of the larva. The histoblasts of the legs, wings, and genitalia are also well developed and approach closely the form of their respective adult organs. A few hours later the stomach opens into the hind-intestine, and its contents are voided in one long, narrow mass. This larval meconium is brown and inclosed in a transparent peritrophic membrane. It is about 1 mm wide and 4 cm long and lies in a convoluted mass at the extreme end of the host abdomen.

Simultaneously with the casting of the meconium a constriction forms in the first abdominal segment. Shortly after the meconium is voided, the last larval skin is cast, thus revealing the pupa.

PUPATION

The newly formed pupa is cream colored. After two days the thorax and later the head turn black, and the adult emerges from its pupal skin. When disturbed, the pupa sways its abdomen slowly back and forth, and if the host case is not too stiff it succeeds in moving that also. The pupal period at a constant temperature of 25° C. (77° F.) averaged four and one-half days.

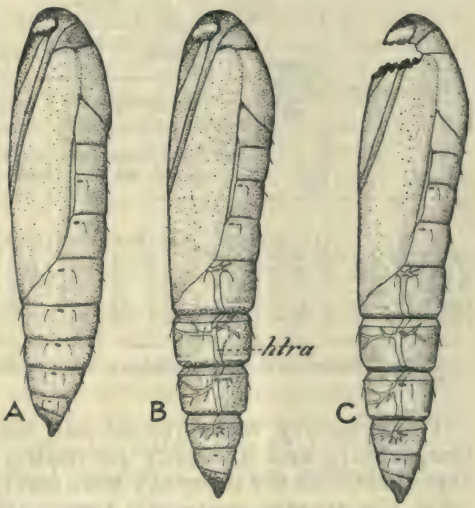


FIGURE 8.—*Pyrausta nubilalis* pupae; A, Either unparasitized or containing a *Phaeogenes nigridens* egg or young larva; B, containing a mature parasite larva; C, pupa from which the parasite has emerged

EFFECT OF PARASITE ON HOST

The first external indication that the Pyrausta pupa has been parasitized occurs when the collapsed host tracheae show through the body wall (fig. 8, B) in the fourth to the sixth abdominal segments. The host is then dead. At the same time these segments become extended by the pressure of the growing larva within, and the sutures between these segments become deeply constricted. Previous to this, when the host was disturbed, the abdomen moved in its normal rapid twisting manner. Now, however, its movements are actuated entirely by the inclosed parasitic larva, which gives it a slow swaying movement that continues long after the external stimulus has stopped. When the parasite reaches the pupal stage, the host case has often dried to such an extent that it can no longer be moved by the parasite.

LENGTH OF LIFE OF ADULT

Both male and female *Phaeogenes nigridens* are very hardy and when placed in an optimum environment live for a long time. In order to determine the longevity of each sex, 124 males and 65 females were subjected, immediately after emergence, to various food, temperature, and humidity conditions. Each individual was confined in a separate cage, of the type already described, and given daily attention until it died. Table 3 summarizes the results of these observations.

TABLE 3.—*Length of life of Phaeogenes nigridens under various conditions of food, temperature, and humidity*

Temperature	Approximate humidity	Males						Females					
		No food			Fed sugar solution			No food			Fed sugar solution		
		Individuals	Longevity		Individuals	Longevity		Individuals	Longevity		Individuals	Longevity	
			Maximum	Average		Maximum	Average		Maximum	Average		Maximum	Average
°C.	Per cent	Number	Days	Days	Number	Days	Days	Number	Days	Days	Number	Days	Days
[1] 27 (80.6° F.)	30–50	10	7	4	11	21	14	4	8	4	4	47	34
25 (77.0° F.)	40–60	13	13	5	11	45	19	8	13	7	5	68	43
18 (64.4° F.)	60–80	8	30	18	15	58	31.5	9	26	14	9	110	70
8 (46.4° F.)	40–60	18	25	12	17	130	83	7	41	22	9	[2] 10	[2] 6
5 (41.0° F.)	60–80	7	22	10	14	152	108	7	39	28	3	[2] 9	[2] 6½

[1] Average temperature of screened insectary, in which this set of experiments was conducted.
[2] Months.

The insectary was screened and subject to all the fluctuations of temperature and humidity prevailing in the Hyères locality. The experiments in the insectary were conducted during July and August, when the average maximum temperature was 33° C. (91.4° F.) and the mean about 27° C. (80.6° F.). The cages having temperatures of 25° C. (77° F.) and 18° C. (64.4° F.) were electrically heated and held at their respective temperatures by an electrothermostat. To obtain the temperatures of 8° and 5° C. (46.4° and 41° F.) the electric refrigerator was used. The temperatures of this cold chamber had a variation at times of 1° C. (1.8° F.) either way. Those adults which were not given food were given no water.

HIBERNATION

P. nigridens passes the winter only as an adult female. The writer has arrived at this conclusion through a series of laboratory and field observations which may be summed up as follows:

It was first definitely proved that neither eggs nor larvae could survive long exposures to temperatures below 12° C. (53.6° F.). Periods of from one to four weeks at these temperatures always resulted fatally to the parasite. When exposed to higher temperatures, development progressed in direct ratio to the temperature, but it was never sufficiently slow to enable either of these stages to bridge the long gap between the fall and spring.

The pupae were able to withstand a longer period of exposure to the temperatures below 12° C. (53.6° F.), but could not survive long enough to pass the winter in this stage. In some cases a slight development took place. At higher temperatures the pupae developed in the same manner as the larvae.

Adult females, on the other hand, have been easily kept on sugar solution in the laboratory at temperatures of from 5° to 8° C. (41° to 46.4° F.) from August to May of the following year, and a few have lived until the middle of June. Males kept under identical conditions always died during the winter.

The hibernation experiment, made under conditions more or less similar to those in the field, was conducted as follows: On August 16, 1930, newly emerged adults (80 males and 70 females) were placed in an outdoor cage measuring 4 by 6 by 5 feet and screened on all sides and the top. The cage was placed in the laboratory yard at Hyères. Mature cornstalks, previously placed within, were sprinkled with water every few days, depending on the rainfall. Sugar solution was also poured over some of the stalks once a week to maintain a constant supply of food. When the cage was examined for the first time, on September 26, all the males and 19 females were dead. The next examination was made March 24, 1931, at which time there were 13 living females. These females died during May, the last one on May 26.

In view of these facts it is believed that *P. nigridens* hibernates only as an adult female.

Of the ichneumonids hibernating as adults, by far the greater number belong to the subfamily Joppinae, according to the records thus far published. Constantineanu (*9*, *p. 418*), in his study of the ichneumonids in Rumania, found only one species outside of this group hibernating as an adult. Morley (*17*, *p. xxviii*) states that hibernating females belong "almost, or quite, exclusively to the Ichneumoninae [now Joppinae] and Cryptinae." Thus far males have never been known to hibernate.

Constantineanu captured hibernating females of each of the following: 40 species of Ichneumon, 4 of Hoplismenus, 4 of Amblyteles, 2 of Chasmias (Chasmodes), and 1 each of Herpestomus, Heterischnus, Stenodontus, and Ischnus. All belong to the same subfamily as Phaeogenes. The specimens were found hidden in the bark or moss of dead trees as well as in the tunnels of xylophagous insects. In the latter part of February, 1927, Constantineanu collected in the field 22 species of females belonging to the foregoing genera. They were placed in cages and fed. Most of them lived until the middle of July of that year, and a few even lived until the middle of August. *P. nigridens* probably hibernates and lives as long as any of the closely allied genera mentioned above.

RATIO OF SEXES

Adults were reared from two summer collections made in northern Italy, and in general the number of females was slightly greater than that of the males. The record of emergence is found in Table 4.

Data on emergence from the second-generation hosts obtained in the spring were too meager to make it possible to determine ac-

curately the proportion of the sexes, but they seem to be about equal at this time also. In the Aquitanian zone, which has usually one generation of the corn borer each year, the males and females also appear to be about equal in number.

TABLE 4.—*Ratio of sexes of Phaeogenes nigridens obtained from summer emergences in Italy*

Year	Locality	Males	Females
		Number	*Number*
1929	Bergamo	36	59
1930	Sermide	79	95
1930	Bergamo	86	79
Total		201	233

PARTHENOGENESIS

Unfertilized females of *P. nigridens* oviposited readily and their eggs developed in the normal manner. The progeny, however, were always males.

SEASONAL HISTORY

With *Phaeogenes nigridens*, which spends the greater part of its life in the adult stage, it is difficult to follow accurately the seasonal history. There apparently is no actual diapause or resting stage in any of the immature stages. As a new generation may be produced every 26 days at 25° C. (77° F.) and every 50 days at 18° C. (64.4° F.), the problem becomes more complicated, particularly when one considers the annual 1- and 2-generation cycle of the host. Since it has been shown to have at least one other host, its true life cycle can not be solved by studying merely the seasonal history of *Pyrausta nubilalis*. It is known, however, that the seasonal history of Phaeogenes follows more or less closely that of Pyrausta in all the zones in which both occur. One parasite generation may extend over at least 11 months, judging by the combination of the maximum length of the immature stages and the maximum life of the female, under conditions more or less comparable with those in the field. Therefore, the parasite is able to reproduce itself with only one generation annually. This would apply to the regions with a low mean summer temperature, such as the Armorican, Rhodanian, and Aquitanian zones. On hosts other than Pyrausta, however, there may be one, and possibly two, additional generations in each of these zones, as fully developed females are always present during July and August.

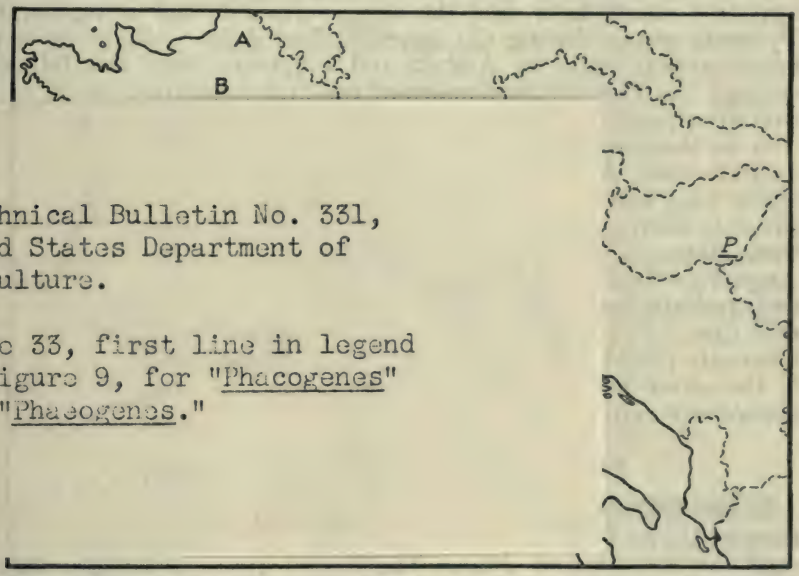
In each zone *Phaeogenes nigridens* passes the winter as an adult female, the males dying before or during the winter.

As the other known host, *Tortrix pronubana* Hbn., occurs in practically all the zones where Phaeogenes is found, it could serve as an intermediate host in those regions where the parasite has more generations than Pyrausta.

The seasonal history of Phaeogenes for the various zones in which it has been studied (fig. 9) is summarized as follows:

ARMORICAN ZONE (TOURS, ANGERS)

In the Armorican zone there is one generation of the host and probably two of the parasite. The overwintering females oviposit in the Pyrausta pupae which appear during May and June. Females of this generation emerge during the latter part of June and the early part of July and, after an oögenetic period of three weeks, lay their first eggs either in the current summer or the following May or June. They may also lay part of their eggs in one summer and the remainder the following spring. As there are no Pyrausta pupae present after the middle of July, the parasite must have an intermediate host in which to lay these summer eggs. The plant in which Pyrausta develops in this zone is *Artemisia vulgaris* L.



Technical Bulletin No. 331, United States Department of Agriculture.

Page 33, first line in legend for Figure 9, for "Phacogenes" read "Phaeogenes."

FIGURE 9.—Map showing the zones in Europe in which *Phacogenes nigridens* has been studied: A, Sequanian (north); B, Sequanian (south); C, Armorican; D, Rhodanian; E, Mediterranean (north); F, Aquitanian; G, Mediterannean (south); H, Padovian (Piedmont); J, Padovian (north); K, Venetian (high); L, Plavisian; M, Venetian (low); N, Padovian (south); and P, Hungarian. Underlined letters represent zones in which the parasite occurs; letters not underlined represent zones from which large host collections have been made but no *P. nigridens* found

RHODANIAN ZONE (JURA)

In the Rhodanian zone the seasonal history is about the same as in the Armorican zone. There is probably a much smaller second generation here, however, as the first adults appear a month later, thus having a much shorter period in which to find suitable hosts. Both corn and Artemisia serve as host plants of Pyrausta in this zone.

AQUITANIAN ZONE (SOUTHWESTERN FRANCE)

In the Aquitanian zone the seasonal history of the parasite is also similar to that in the Armorican zone. The only difference is that in some years there is a partial second generation of the host, and in that

case there will be two generations on Pyrausta. No investigations were made definitely to prove this conclusion, but as laying females are present all summer it seems quite probable. The adults emerge in the latter part of June or early part of July and lay their eggs either in the following month or in the succeeding May or June, at which time Pyrausta pupae are available. Corn is the chief food plant of Pyrausta in this zone.

MEDITERRANEAN (SOUTH) ZONE (HYÈRES)

In the Mediterranean zone there are regularly two full generations of the host and two of the parasite. The females from the previous year lay eggs in the first Pyrausta pupae that appear in the latter part of April and the first part of May. Adults of this generation appear a month later, and the eggs are laid in the first-generation Pyrausta pupae during the latter half of July. Adults from this brood appear early in August and hibernate until the following spring. As Phaeogenes females of the first generation are in condition to oviposit during June, there is a possibility of a second generation at this time either on late Pyrausta pupae or on some intermediate host. Adults from this generation would appear about three weeks later and the eggs laid in pupae of the second host generation present, during the latter half of July. Females emerging from these pupae could have a fourth brood during the latter part of August or first part of September, but it would have to be on an intermediate host as there are usually no Pyrausta pupae present at this time. Females of this possible fourth generation would then hibernate until the following spring before laying their eggs. Corn is the chief host plant of Pyrausta in this zone, but it is not extensively cultivated.

PADOVIAN (PIEDMONT) ZONE (TURIN)

In the Padovian (Piedmont) zone there are normally two generations of the host and two of the parasite. Overwintering females lay eggs the first part of June. The second generation begins late in July, and females from this generation lay eggs the following spring. There may be a partial third generation on another host late in August. Corn is the chief host plant of Pyrausta in this zone.

PADOVIAN (NORTH) ZONE (BERGAMO, PAVIA, MANTOVA)

The Padovian (north) is also a 2-generation zone for both host and parasite, although in some years there is a possibility of a partial third parasite generation on an intermediate host at the end of the summer. The adults lay their eggs in the latter part of May. The second generation begins in the middle of July, and the resulting adults oviposit the following spring. The most detailed studies of the seasonal history of Phaeogenes have been made in this zone, particularly around Bergamo, and all the data show that the parasite has only two generations on Pyrausta. The notes were all based on field observations. By comparing the knowledge of the time of first emergence, length of life, habits, etc., of Phaeogenes with the seasonal history of the host, it will be readily seen that there can occur a

partial third generation on the Pyrausta pupae present in the late summer. As field observations did not bear this out, it does not enter into the data used in Figure 10, which shows the seasonal history of Pyrausta and Phaeogenes as determined from field observations and laboratory rearings. Corn is the principal host of Pyrausta in this zone and is cultivated extensively. Of all the Pyrausta-infested regions of Europe this zone most closely approaches the climatic conditions of the corn-borer-infested districts in New England. It is characterized by rather long, cold winters

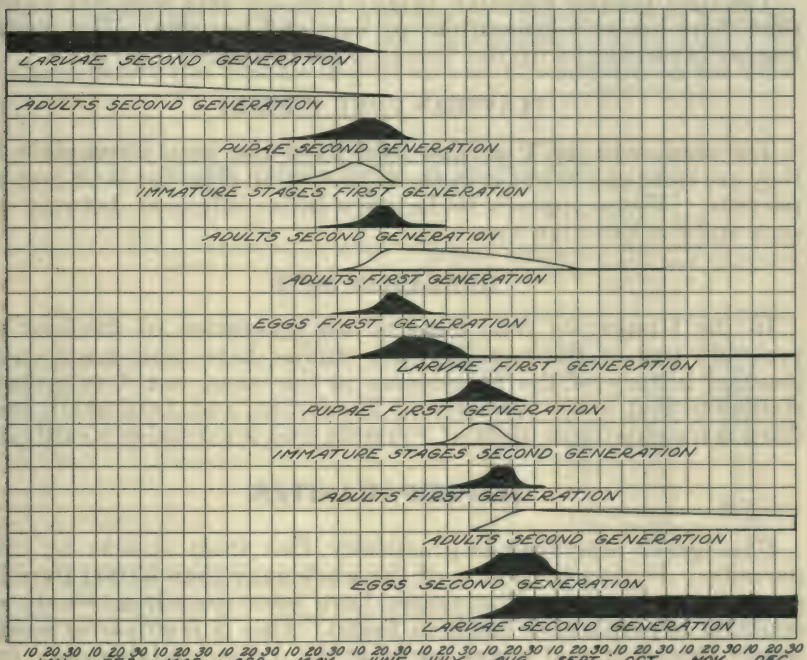

LARVAE SECOND GENERATION
ADULTS SECOND GENERATION
PUPAE SECOND GENERATION
IMMATURE STAGES FIRST GENERATION
ADULTS SECOND GENERATION
ADULTS FIRST GENERATION
EGGS FIRST GENERATION
LARVAE FIRST GENERATION
PUPAE FIRST GENERATION
IMMATURE STAGES SECOND GENERATION
ADULTS FIRST GENERATION
ADULTS SECOND GENERATION
EGGS SECOND GENERATION
LARVAE SECOND GENERATION
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20 30
JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC.

FIGURE 10.—Seasonal history of *Pyrausta nubilalis* and its parasite, *Phaeogenes nigridens*, based on field observations and laboratory rearings. Black areas represent *P. nubilalis*, and the clear areas represent *P. nigridens*

with abundant snowfall, and short, hot summers with occasional heavy rainfall. All the important parasites of this zone have also been recovered from the New England area.

PADOVIAN (SOUTH) ZONE (PIACENZA, FERRARA, SERMIDE)

The Padovian (south) zone is similar to the Padovian (north) zone. Both Pyrausta and its parasite have two generations. Pupation of the host begins about two weeks earlier in the spring and summer than in the Padovian (north) zone, and the development of the parasite is synchronized with it. Both corn and hemp serve as host plants of Pyrausta in this zone, but the latter plant supports only the first generation of the borer, as it is cut before the second generation can attack it.

VENETIAN (LOW) ZONE (PADUA)

The data for the Venetian (low) zone are somewhat meager, but it is known that there are at least two generations. The climate and agriculture are practically identical with those of the Padovian (south) zone. The seasonal history is also the same as in the Padovian (south) zone. Corn is the chief host plant.

VENETIAN (HIGH) ZONE (TREVISO)

The data for the Venetian (high) zone are only sufficient to show that there are two generations of host and parasite. The seasonal history is identical with the Venetian (low) zone.

PLAVISIAN ZONE (UDINE)

The studies in the Plavisian zone have also been incomplete, but they are sufficient to put it in the 2-generation class for both host and parasite. There appears to be very little difference between this zone and the Venetian zone.

HUNGARIAN ZONE

In the Hungarian zone there is one generation of the host and probably two of the parasite. No studies have been made on the seasonal history of the Phaeogenes in this zone, but it is probably similar to that in the Armorican, Rhodanian, and Aquitanian zones. Corn is the chief host plant of Pyrausta and is extensively cultivated.

HYPERPARASITES

Phaeogenes nigridens is practically free from attacks by other parasites. During the course of the work more than 65,000 Pyrausta pupae parasitized by Phaeogenes have been reared, and only one doubtful hyperparasite has been found. This is *Haltichella maculipennis* Destefani, and it was reared at the Arlington laboratory from Pyrausta pupae collected in Italy and supposedly parasitized by Phaeogenes.

Goidanich (*13*) recorded rearing a gregarious pteromalid species from Pyrausta pupae, but he could not confirm it as a parasite on Phaeogenes. It is probably not parasitic on Phaeogenes, however, as the writer has reared from healthy pupae a number of specimens of a gregarious pteromalid identified as *Dibrachys* sp. This species was later bred in the laboratory on unparasitized Pyrausta pupae.

PHAEOGENES NIGRIDENS AS A CONTROLLING FACTOR OF PYRAUSTA NUBILALIS

Phaeogenes nigridens is widely distributed in Europe, but its degree of effectiveness on *Pyrausta nubilalis* appears relatively low in all the regions outside of northern Italy. In the Padovian (north) zone of this area, where the most consistent studies of this parasite have been made, the records show that from 1924 to 1927, inclusive, and

in 1930 *Phaeogenes nigridens* had annually the highest percentage of parasitism of all the *Pyrausta nubilalis* parasites. In 1928 the total parasitism by all species was about the same as its average for other years, but the parasitism by *Phaeogenes nigridens* fell much below its yearly average. It was even surpassed in this year by two other species, *Angitia* (*Inareolata*) *punctoria* Roman and *Microgaster tibialis* Nees. In 1929 the total parasitism dropped to almost half what it usually was, but only *A. punctoria* exceeded *P. nigridens* in parasitism.

In the other European zones the degree of parasitism remains more or less constant, although occasionally it goes to zero for some years, as has been the case in the Mediterranean (south) zone.

Table 5 shows the relative importance of *P. nigridens* in the various zones.

TABLE 5.—*Average and maximum parasitism by Phaeogenes nigridens in Europe for the period of investigations*

Zone	Average parasitism	Maximum parasitism [1]	Year in which maximum parasitism occurred	Host plant
	Per cent	*Per cent*		
Padovian (Piedmont) [2]	12.89	12.89	1930	Corn.
Padovian (north)	7.73	17.50	1927	Do.
Padovian (south)	6.23	7.34	1930	Hemp.
Plavisian	1.85	4.60	1928	Corn.
Armorican [2]	1.43	1.43	1929	Artemisia.
Padovian (south)	1.33	2.70	1925	Corn.
Venetian (high) [2]	1.20	1.20	1928	Do.
Aquitanian	.79	3.15	1930	Do.
Venetian (low)	.70	1.90	1928	Do.
Rhodanian	.35	.70	1925	Artemisia.
Mediterranean (coast)	.14	[3].84	1921	Corn.
Rhodanian	.12	[3].25	1925	Do.

[1] The maximum parasitism was always in the first generation.
[2] Only one year's observation available.
[3] Computed from additional data obtained since the publication of earlier records of Thompson and Parker (27).

Table 6 shows in detail, by year and generation, the percentage of parasitism of Pyrausta by *Phaeogenes nigridens* as observed in corn, Artemisia, and hemp in the various zones during the years in which it has been studied. It should be borne in mind that, although the figure for the average parasitism in the Padovian (Piedmont) zone for 1930 is slightly higher than that in the Padovian (north) zone for the same year, the figure was based on only 450 individuals as against 2,200 for the latter zone.

The highest percentage of parasitism of the first generation of Pyrausta is found in the earliest sown fields, which also have usually the heaviest corn-borer infestation. In determining this point, observations were made in three adjacent cornfields near Bergamo in the summer of 1930, after the Pyrausta pupation was practically complete. The results are summarized in Table 7. Observations made at Turin in the same summer gave similar results, and these are also given in Table 7. In this latter case, however, the dates of planting were not known, and the cornfields were several miles apart.

TABLE 6.—*Percentage of parasitism of Pyrausta nubilalis by Phaeogenes nigridens in corn, Artemisia, and hemp in the various zones of Europe for 1921–1930* [1]

Year	Generation	Mediterranean coast, corn	Aquitanian, corn	Rhodanian		Armorican, corn	Padovian				Venetian		Plavisian, corn
				Corn	Artemisia		Piedmont, corn	North, corn	South		High, corn	Low, corn	
									Corn	Hemp			
		P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.
1921	1	0.84											
1922	1	.48											
1923	1	.09											
1924	1			0	0			6.70					
1925	1	.40	0.01	.25	.70			14.00	2.70				
1926	1	0	0					8.10					
	2	0											
1927	1	0	0					17.50					
	2	0											
1928	1	0				1.43		4.30			1.20	1.90	4.60
	2	0						1.25					
1929	1	0	3.15					2.49	1.29	5.13		.21	.33
	2	0						2.78					.63
1930	1	0					12.89	12.44	0	7.34		0	

[1] Spaces in which no figures are found indicate that no studies were made.

TABLE 7.—*Parasitism by Phaeogenes nigridens in early and late planted cornfields near Bergamo and Turin, Italy, 1930*

Locality	Field No.	Date planted	Date examined	Degree of maturity of corn		Infestation by *Pyrausta nubilalis* [1]	Hosts studied	Parasitism by *Phaeogenes nigridens*
				Tassels	Silk			
						Per cent	Number	Per cent
Bergamo	1	Apr. 3	Aug. 1	Dry	Dry	70	842	21.49
	2	Apr. 7	do	In flower	Not dry	53	266	8.27
	3	Apr. 9	Aug. 2	do	do	25	429	3.49
Turin	1	Unknown	Aug. 11	do	do	15	104	2.89
	2	do	do	Dry	Dry	44	60	16.66
	3	do	do	do	do	81	124	19.03
	4	do	do	do	do	62	162	12.96

[1] The number of plants examined in each instance was 200.

With the second generation of Pyrausta, where both Pyrausta and Phaeogenes occur, the highest percentage of parasitism is found among those cornstalks lying outside the barns.

LIMITING FACTORS IN EFFECTIVENESS OF PHAEOGENES NIGRIDENS

An important limiting factor is probably the very low reproductive rate of *Phaeogenes nigridens* as compared with that of *Pyrausta nubilalis*. It was not possible to determine the potential number of eggs in the female ovaries, but the average number deposited in the laboratory was 6; the maximum number was 11. These figures are probably much lower than they would be in the field, but at the most it appears that a *Phaeogenes nigridens* female does not lay more than 50 eggs.

Experiments have shown conclusively that, when the eggs have become mature in the ovaries of the *Phaeogenes nigridens* female and

remain undeposited after a week or so, the eggs will die, disintegrate, and pass out through the oviduct. In the summer there is probably sufficient host material so that this destruction of the eggs takes place only occasionally. In the long hibernating period of the female from August until the following spring, however, the eggs continue to develop slowly, and before the spring oviposition period arrives many eggs will have matured and died, the number varying in direct ratio to the temperature.

The Phaeogenes female possesses a very short ovipositor, projecting only slightly beyond the tip of the abdomen, and therefore can attack only those individuals into whose tunnels she is able to penetrate. As the female requires from 11 days to 4 weeks to get into condition to oviposit, this further reduces her effectiveness. The long hibernation period of the females, with its consequent mortality, must also greatly lower the importance of this species as a controlling factor of Pyrausta.

Another limiting factor, operating particularly in northern Italy, is the practice of storing the cornstalks in a shed. All experiments have shown that Pyrausta pupae in stalks kept under these conditions are comparatively free from attack by Phaeogenes. The only breeding places that the parasite can find are infested stalks used around the buildings for protection against the cold, the few corn stacks that happen to be left outside, and the odd pieces of infested stalks lying around outside of barns and on the fields.

Hyperparasitism does not constitute a limiting factor, as there is only one record of such occurrence among the thousands of parasitized pupae reared, and that record is doubtful.

Phaeogenes, a parasite of the corn-borer pupa, is not subjected to competition, as are the parasites of the egg and larva. The other parasites attacking the pupal stage of Pyrausta have been reared only at rare intervals and in negligible numbers, and can not, therefore, be considered as serious factors in controlling Pyrausta. For the same reason they can not be considered as detrimental to Phaeogenes.

COLLECTION AND SHIPMENT OF THE PARASITE

Although *P. nigridens* was found to occur near Hyères in 1922, no gross collecting operations were possible until it was discovered by H. L. Parker in large numbers near Bergamo, Italy, in the summer of 1924. In that year the first collection of larval parasites of the corn borer was begun in this district, and along with them were collected several thousand pupae which were brought back to the Hyères laboratory. From these pupae 1,683 adult parasites issued, and 1,601 were sent to the United States. Since then shipments have been made annually from this district, the average percentage of emergence after arrival in the United States being 38.5.

The first shipment was made with freshly emerged adults in small glass lantern globes. They were fed just previous to shipment, and no food was supplied en route. The globes were securely packed and carried to Cherbourg in refrigerator valises identical with those originated by the gipsy moth laboratory (*4*, *p. 101*). Arriving at the port, they were placed in the refrigerator room of the first passenger ship sailing to New York. From there they were re-

shipped to the Arlington laboratory, located just outside of Boston. The entire trip from Hyères to Arlington consumed from 9 to 10 days. Only a few of the adults died en route, and these were practically all males.

The following year collections of all parasites were made as in the previous year, but the parasitized pupae were separated from the unparasitized ones in the field laboratory at the base of operations. The entire procedure was as follows: The date on which to begin work was first established by making field collections in the latter part of July to determine when most of the other parasites of the corn borer had formed their cocoons and puparia. The time when host pupation had reached about 60 per cent was fixed as the correct date. On August 3 about 150 peasants were assembled, and to each was issued a small can, having a hole in the cover through which to drop the pupae, and a box for the other parasites. The workers scattered over the district and made collections in any field they chose. At the end of each day the pupae were brought in, counted, placed in shallow trays covered on the bottom with wire netting, and stored in a cool cellar. The next day women separated the parasitized pupae from the others and placed them in flat cardboard boxes 5.5 by 0.9 cm. The boxes were then packed in larger wooden ones and taken to Genoa in the refrigerator valises. At Genoa they were placed in the cheese or vegetable room of the first passenger boat sailing for New York or Boston. From the time of collection of the parasites till their arrival at Arlington, a period of 15 to 23 days, the temperature ranged from 4° to 10° C. (39.2° to 50° F.), most of the time being near the lower temperature.

The percentage of adult emergence [11] from the 1925 shipment was 44.7. In 1926, 1927, and 1928 the methods of collecting and shipping were the same as in 1925. The percentage of emergence at Arlington for these shipments was 36.6 in 1926, 37.2 in 1927, and 37.2 in 1928.

In 1929 several different methods of packing the parasitized pupae were tried, but the results did not warrant the use of any of them. The technic was in other respects the same as in the previous years. The emergence for this year was 37 per cent.

In 1930 the collection of the other parasites from the Bergamo district was discontinued and only *Phaeogenes nigridens* collected. This permitted collections to be made under optimum conditions. Theretofore it had become necessary to begin the work while many individuals of *Phaeogenes nigridens* were in the larval stage. This resulted in high mortality when they were exposed to the cold temperature necessary for shipment. Many others also died because of drying out in the trays.

To fix the date on which to begin work under these changed conditions, several hundred pupae were collected during the last week of July and dissected to determine the stage in which most of the Phaeogenes were. When the majority were found to be in the late mature larval or young pupal stage, collecting on a large scale was begun. This date coincided approximately with a host pupation of 80 per cent and a moth emergence of 20 per cent. The entire work was confined to a relatively short period in order to keep as many of the parasites as possible from emerging before being placed in cold

[11] The notes on adult emergence were supplied by D. W. Jones, of the Arlington (Mass.) laboratory.

storage. Males preceded females in emergence by three or four days and continued to predominate until the end of a week, so collections could be made several days after the appearance of the first adult without undue loss. Collections for this year began on July 29 and ended August 6.

The methods of packing used in the summer of 1930 differed from any previously used in that they provided for the feeding of the parasites that emerged en route. This embodied the principle of the nondripping feeding tube as developed at the European branch of the gipsy moth laboratory (*4, p. 93*) in Budapest, Hungary. The wooden box used in other years was arranged inside so as to accommodate five flat wooden partitions, placed equidistant from each other, which could be moved in or out. Two feeding tubes were nailed to the inside of each box cover. The design of the flat cardboard boxes was changed somewhat in order to give the emerged parasites a more nearly ideal environment. A large square opening was cut in the cover of each box and a piece of mosquito netting glued across this opening on the inside. The holes in the netting were just large enough to allow the parasite to push itself through.

In preparing the boxes for shipment, the nickeled-brass feeding tubes, containing a wick slightly longer than the tube, were filled with saturated sugar solution and tightly plugged with cotton. In the meantime the cardboard boxes were filled with the parasitized pupae and tied to each side of the partitions. The latter were then slid into place and the cover nailed down.

By this means not only are food and ample resting places supplied for any adult parasites which may emerge en route, but since there is always a certain small percentage of nonparasitized pupae in the boxes, the resulting moths are also prevented from filling the air with their fine scales.

The percentage of emergence en route for this shipment was 6.6 and the mortality 3.1. The percentage of emergence for the entire shipment was 38.4. The number of days from collection to arrival at Arlington was from 13 to 21. In every case the feeding tubes were still moist at the end of the trip.

A small shipment of parasitized pupae collected in hemp was also made from Sermide, in the Padovian (south) zone, by H. L. Parker. This collection, however, was merely incidental to the main project, which was to collect and ship the chalcid *Eulophus viridulus* Thoms., an external parasite of *Pyrausta nubilalis* larvae.

After several seasons of experiments with different shipping methods, the writer concludes that the optimum conditions for the parasitized pupae are a temperature range of from 14° to 18° C. (57.2° to 64.4° F.) and a humidity of from 50 to 70 per cent, which allows the immature stages to develop slowly and at the same time prolongs the life of the adults. This procedure will be put into practice in making future shipments.[12]

[12]As it was impossible to obtain the optimum temperature of 14° to 18° C. (57.2° to 64.4° F.) on board any ship from Genoa, the collecting and shipping technic used in 1930 was changed in 1931 to allow the parasites to develop normally until they were placed (at sailing time) in the ship's refrigerator room at a temperature of from 4° to 10° C. (39.2° to 50° F.) To feed the greatly increased number of adults, two 150 c c bottles containing sugar solution were stoppered with large plugs of cotton and secured to a rack nailed to the inside of the usual shipping box. A total of 7,300 parasitized *P. nubilalis* pupae and 1,074 adults were shipped under these conditions. The percentage of emergence for this shipment at the Arlington (Mass.) laboratory was 62.5, an increase of 24 per cent over the average emergence of other years.

As the Bergamo district is an industrial center with correspondingly high wage scales, other areas have been scouted at various times to locate, if possible, additional sources having a lower cost per parasite for collection, but thus far none has been found. Practically the whole of northern Italy and the Aquitanian and Rhodanian zones in France have been surveyed and, although the parasite has been found occasionally in sufficient quantities, other factors have always entered which made the cost of collection higher than at Bergamo.

SUMMARY

The ichneumonid *Phaeogenes nigridens* Wesm. is the most important parasite of the pupal stage of the European corn borer in Europe. It occurs in Sweden, Germany, Belgium, France, Italy, and Hungary.

The adult is distinguished from the other parasites of the corn borer by its robust appearance, its rusty red-brown abdomen with black terminal portion and, in the female, the white band around the middle of the antennae. The female reproductive organs have three polytrophic ovarioles in each ovary, a spermatheca, and two accessory glands. The egg is hyaline, oblong-ovate, slightly arched, and entirely smooth.

The larva has at least four distinct instars. There is a possibility of a fifth instar, but the evidence is insufficient. The primary larva is robust, segmented, and has a large, heavily sclerotized head with long, hooked mandibles. The cuticle of the body is covered with many definitely arranged setae and spines. There are no spiracles in this instar. The head of the secondary larva is much shorter, less sclerotized, and has a large ventral protuberance. There are nine pairs of functionless spiracles. The tertiary larva is distinguished from the previous stages by its larger mandibles and spiracles, the absence of the ventral protuberance on the head, and the disappearance of the integumentary spines. Each of the last three abdominal segments has a band of minute rugosities extending around the middle of the segment.

The mature larva is light pink or tan and has a prominent hump dorsally in the third thoracic and first abdominal segments. The ventral region of the head is unpigmented and only lightly sclerotized. There are numerous epidermal thickenings and structures of the head skeleton with a definite arrangement and function which may serve the purpose of future larval determinations. The first seven pairs of spiracles function during the entire instar, but the eighth and ninth pairs are not open until the larva is nearly mature. The muscles of the head are divided into five distinct groups and the integumentary ones of the trunk into eight. The latter are somewhat complicated.

Pupation takes place within the host pupa, the abdomen of which has been extended by the growing larva within. The latter character serves to identify the pupae.

The adults feed on honey, raisins, dry sugar, or weak sugar solution, and occasionally on the blood of the host. Mating is easily secured with young adults. Females kept at 25° C. (77° F.) require an oögenetic period of from one to two weeks.

The female oviposits only in the pupal stage of Pyrausta and shows a preference for the freshly formed pupae. Usually only one egg is deposited in a host. Both egg and larva float freely within the body of the host, entirely unaffected by the phagocytes of the latter. At first the larva feeds on the blood and fat of the host, later attacking the vital organs. The entire period from egg to adult at a temperature of 25° C. (77° F.) is about 15 days.

The adults are very long lived, some females having been kept alive at low temperature for about 10 months. Hibernation occurs in the adult stage.

The seasonal history of *Phaeogenes nigridens* synchronizes closely with that of Pyrausta in all the European zones. It can survive with only one generation a year, as may be necessary in the 1-generation host zones, but as it is known to have at least one other host (one specimen having been reared from *Tortrix pronubana* Hbn.), it may have two or more generations in any of these zones, the additional ones being on the intermediate host. In the 1-generation areas the overwintering female lays its eggs in the Pyrausta pupae formed in the spring and emerges three or four weeks later, depending on the temperature. These females either hibernate or lay eggs in an intermediate host in the same summer. In the 2-generation host zones the hibernating females oviposit in the host pupae and the resulting females attack the summer pupae formed in July and August. The females of this brood then hibernate until the following spring. In these regions there is also a possibility of one or two extra generations on an intermediate host owing to the presence of laying females in the field at all times.

Of all the regions in Europe, the area in which the parasite is most effective is the Padovian (north) zone in northern Italy, where the climatic conditions approach most closely those of the corn-borer area of New England. In this zone *Phaeogenes nigridens* had annually from 1924 to 1927, inclusive, and in 1930, the highest percentage of parasitism of any Pyrausta parasite. The maximum parasitism of the host that has thus far been recorded is 17.5 per cent. The parasite has been found in Pyrausta pupae in corn, Artemisia, and hemp.

Factors that may limit the effectiveness of this species are the small number of eggs produced by each female; the mortality of some ovarian eggs, especially among hibernating females; the rather long oögenetic period; and the generally unsuitable oviposition conditions in the spring.

Shipments of the parasite have been made annually since 1924. The first shipment was made in the adult stage and the others in the pupal stage inside the host pupa. All shipments were kept at from 4° to 10° C. (39.2° to 50° F.) during the period between their collection and their receipt at Arlington. The average percentage of emergence after arrival in the United States was 38.5.

LITERATURE CITED

(1) ANONYMOUS.
1927. CURRENT NOTES. [PYRAUSTA NUBILALIS.] Jour. Econ. Ent. 20: 761.

(2) ASHMEAD, W. H.
1900. CLASSIFICATION OF THE ICHNEUMON FLIES, OR THE SUPERFAMILY ICHNEUMONOIDEA. U. S. Natl. Mus. Proc. 23: 1–220.

(3) BERTHOUMIEU, G. V.
1894–1896. ICHNEUMONIDES D'EUROPE ET DES PAYS LIMITROPHES. 1re TRIBU.—ICHNEUMONIENS. Ann. Soc. Ent. France 63: [241]–274, 505–664, 1894; 64: 213–296, 553–654, 1895; 65: [285]–418, illus., 1896.

(4) BURGESS, A. F., AND CROSSMAN, S. S.
1929. IMPORTED INSECT ENEMIES OF THE GIPSY MOTH AND THE BROWN-TAIL MOTH. U. S. Dept. Agr. Tech. Bul. 86, 148 p., illus.

(5) CAFFREY, D. J., AND WORTHLEY, L. H.
1927. A PROGRESS REPORT ON THE INVESTIGATIONS OF THE EUROPEAN CORN BORER. U. S. Dept. Agr. Bul. 1476, 155 p., illus.

(6) ——— and WORTHLEY, L. H.
1927. THE EUROPEAN CORN BORER: ITS PRESENT STATUS AND METHODS OF CONTROL. U. S. Dept. Agr. Farmers' Bul. 1548, 48 p., illus.

(7) CEBALLOS, D. G.
1925. HIMENÓPTEROS DE ESPAÑA. FAMILIA ICHNEUMONIDÆ. Mem. R. Acad. Cien. Exact., Físicas y Nat. Madrid 31, 292 p., illus.

(8) CHEWYREV, I. J.
1912. [PARASITES AND HYPERPARASITES IN THE INSECT WORLD.] Messager Ent. 1: 1–77, illus. [In Russian.]

(9) CONSTANTINEANU, M. I.
1929. CONTRIBUTIONS A L'ÉTUDE DES ICHNEUMONIDÉS EN ROUMANIE. Ann. Sci. Univ. Jassy 15: [387]–641, illus.

(10) CUSHMAN, R. A.
1926. SOME TYPES OF PARASITISM AMONG THE ICHNEUMONIDAE. Ent. Soc. Wash. Proc. 28 (2): 29–51, illus.

(11) DALLA TORRE, C. G. DE
1901–2. CATALOGUS HYMENOPTERORUM HUCUSQUE DESCRIPTORUM SYSTEMATICUS ET SYNONYMICUS. v. 3, 1141 p. Lipsiae.

(12) FISKE, W. F.
1903. A STUDY OF THE PARASITES OF THE AMERICAN TENT CATERPILLAR. N. H. Agr. Expt. Sta. Tech. Bul. 6: [185]–230, illus.

(13) GOIDANICH, A.
1928. CONTRIBUTI ALLA CONOSCENZA DELL'ENTOMOFAUNA DELLA CANAPA. Bol. Lab. Ent. R. Ist. Super. Agr. Bologna 1: [37]–64.

(14) JONES, D. W.
1927. STATUS OF IMPORTED PARASITES OF THE EUROPEAN CORN BORER. U. S. Dept. Agr. Circ. 14, 8 p., illus.

(15) ———
1929. IMPORTED PARASITES OF THE EUROPEAN CORN BORER IN AMERICA. U. S. Dept. Agr. Tech. Bul. 98, 28 p., illus.

(16) MEÏER, [N. F.]
1928. ON THE BIOLOGY OF PARASITES OF FELTIA SEGETUM, SCHIFF. Izv. Otd. Prikl. Ent. 3 (2): 201–218. illus. [Original not seen.] Abstract in Rev. Appl. Ent. 17: 140–141.

(17) MORLEY, C.
1903. ICHNEUMONOLOGIA BRITANNICA. THE ICHNEUMONS OF GREAT BRITAIN; A DESCRIPTIVE ACCOUNT OF THE FAMILIES, GENERA AND SPECIES INDIGENOUS TO THE BRITISH ISLANDS, TOGETHER WITH NOTES AS TO CLASSIFICATION, LOCALITIES, HABITATS, HOSTS, ETC. ICHNEUMONINAE. 315 p., illus. Plymouth.

(18) PAMPEL, W.
1914. DIE WEIBLICHEN GESCHLECHTSORGANE DER ICHNEUMONIDEN. Ztschr. Wiss. Zool. 108: [290]–357, illus.

(19) PARKER, H. L., VANCE, A. M., SMITH, H. D., AND GAMKRELIDZE, W.
1929. PYRAUSTA NUBILALIS HUBN. IN EUROPE: NOTES ON INFESTATION AND PARASITISM FROM 1926 TO 1928. Jour. Econ. Ent. 22: 688–693.

(20) POUTIERS, R.
1927. LES PARASITES DE LA TORDEUSE DE L'ŒILLET, TORTRIX PRONUBANA HB. Rev. Path. Vég. et Ent. Agr. 14: [224]–227.

(21) RATZEBURG, J. T. C.
1844–1852. DIE ICHNEUMONEN DER FORSTINSECTEN IN FORSTLICHER UND ENTOMOLOGISCHER BEZIEHUNG; EIN ANHANG ZUR ABBILDUNG UND BESCHREIBUNG DER FORSTINSECTEN. 3 v., illus. Berlin.

(22) SACHTLEBEN, H.
1930. ON THE PARASITES OF PYRAUSTA NUBILALIS HB. IN HUNGARY. Internatl. Corn Borer Invest. Sci. Rpts. 3: 101–112, illus.

(23) SCHMIEDEKNECHT, O.
1907. DIE HYMENOPTEREN MITTELEUROPAS . . . 804 p., illus. Jena.

(24) SEURAT, L. G.
1899. CONTRIBUTIONS À L'ÉTUDE DES HYMÉNOPTÈRES ENTOMOPHAGES. 159 p., illus. Paris. (Thèse, Faculté des Sciences.)

(25) SILVESTRI, F.
1923. CONTRIBUZIONI ALLA CONESCENZA DEI TORTRICIDI DELLE QUERCE. (I–II) Bol. Lab. Zool. Gen. e Agr. R. Scuola Super. Agr. Portici 17: [41]–107, illus.

(26) STRICKLAND, E. H.
1923. BIOLOGICAL NOTES ON PARASITES OF PRAIRIE CUTWORMS. Canada Dept. Agr. Bul. (n. s.) 26 (Ent. Bul. 22), 40 p., illus.

(27) THOMPSON, W. R., AND PARKER, H. L.
1928. THE EUROPEAN CORN BORER AND ITS CONTROLLING FACTORS IN EUROPE. U. S. Dept. Agr. Tech. Bul. 59, 63 p., illus.

(28) ——— AND PARKER, H. L.
1930. THE MORPHOLOGY AND BIOLOGY OF EULIMNERIA CRASSIFEMUR, AN IMPORTED PARASITE OF THE EUROPEAN CORN BORER. Jour. Agr. Research 40: 321–345, illus.

(29) THORPE, W. H.
1930. OBSERVATIONS ON THE PARASITES OF THE PINE-SHOOT MOTH, RHYACIONIA BUOLIANA, SCHIFF. Bul. Ent. Research 21 (pt. 3): 387–412, illus.

(30) TIMBERLAKE, P. H.
1912. TECHNICAL RESULTS FROM THE GIPSY MOTH PARASITE LABORATORY. V. EXPERIMENTAL PARASITISM: A STUDY OF THE BIOLOGY OF LIMNERIUM VALIDUM (CRESSON). U. S. Dept. Agr., Bur. Ent. Tech. Ser. 19 (pt. 5): 71–92, illus.

(31) TOTHILL, J. D.
1922. THE NATURAL CONTROL OF THE FALL WEBWORM (HYPHANTRIA CUNEA DRURY) IN CANADA TOGETHER WITH AN ACCOUNT OF ITS SEVERAL PARASITES. Canada Dept. Agr. Bul. (n. s.) 3 (Ent. Bul. 19), 107 p., illus.

(32) WESMAEL, C.
1844. TENTAMEN DISPOSITIONIS METHODICAE ICHNEUMONUM BELGII. Acad. Roy. Belg. Mem. 18, [no. 2], 238 p., illus.

(33) ———
1848. MANTISSA ICHNEUMONUM BELGII. Acad. Roy. Belg. Bul. 15 (pt. 1): 292–341.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Weather Bureau	CHARLES F. MARVIN, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Forest Service	R. Y. STUART, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Plant Quarantine and Control Administration	LEE A. STRONG, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*

This bulletin is a contribution from

Bureau of Entomology	C. L. MARLATT, *Chief.*
Division of Cereal and Forage Insects	W. H. LARRIMER, *Principal Entomologist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - Price 5 cents

TECHNICAL BULLETIN No. 330 NOVEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

ROTATION AND TILLAGE EXPERIMENTS AT THE LAWTON (OKLA.) FIELD STATION, 1917–1930

By W. M. OSBORN

Associate Agronomist, Division of Dry Land Agriculture, Bureau of Plant Industry

CONTENTS

	Page
Introduction	1
Crops grown in the region	2
Description of the station	3
Climatic conditions	4
Rotation and tillage experiments	6
Results with corn	7
Results with kafir	10
Results with sorgo	15
Results with feterita	17
Results with milo	19
Results with corn, kafir, sorgo, and feterita under continuous cropping	19
Rotation and tillage experiments—Continued.	Page
Results with broomcorn	21
Results with cotton	21
Results with wheat	25
Results with oats	28
Results with barley	29
Comparative yields of wheat, oats, and barley	29
Results with cowpeas	30
Results with alfalfa	32
Results with sweetclover	33
Results with peanuts	33
Summary and conclusions	33

INTRODUCTION

In 1915 the Division of Dry Land Agriculture of the United States Department of Agriculture established and began operating the United States Dry Land Field Station near Lawton, in southwestern Oklahoma, close to the eastern limit of the southern Great Plains. The altitude of the station is approximately 1,150 feet, and the annual precipitation there is nearly 31 inches.

The station at Lawton is representative of a large area in southwestern Oklahoma and northern Texas. No other extensive area in the Great Plains is directly comparable or similar to that in which the Lawton station is located. The average precipitation is heavy enough to warrant the general classification of the section as subhumid rather than semiarid, but it is not so dependable as in other sections where the average is lower. The rainfall is often torrential, and its monthly distribution is variable. The summers are frequently long and hot, and more or less protracted periods of drought are common. Conditions highly favorable to the growth of tender vegetation may suddenly change to conditions that are common to arid regions where plant growth is continually dwarfed and stunted.

Soils differ widely in structure and composition in this section, where erosion is great enough to be a problem on most farms.

Destructive insects frequently take a heavy toll of one or more crops and reduce the farm revenues to a small margin of profit and

129789°—32——1

often cause loss. The chief insect enemies are the chinch bug (*Blissus leucopterus*), the boll weevil (*Anthonomus grandis*), and several species of worms.

This part of the State is drained by a great many intermittent streams flowing in a southerly direction. These streams are small, but occasionally overflow, with considerable damage to adjacent farm lands. They are usually bordered with some timber, which is used chiefly for fuel. Some pecans grow and are harvested in these belts of timber. Adjacent to the creeks and rivers there is much valuable farm land with a productive soil that responds readily and dependably to good husbandry.

The section is comparatively new, much of southwestern Oklahoma having been opened to the home seeker in 1901. It has undergone a rapid and permanent development in the transition from well-grassed plains, that supported large herds of grazing beef cattle, to the plow and the small home farm. Crop practices and farm operations have been gradually adapted to meet climatic demands and other hazards. Wherever the human effort in this scheme of development has been directed aggressively, persistently, carefully, and intelligently, farm life has been attended with a moderate degree of success.

CROPS GROWN IN THE REGION

A large variety of crops is grown, each crop occupying a place in farm practice determined by its adaptability to individual farm needs and plans and to the equipment and facilities for handling it.

Alfalfa is grown quite successfully on bottom land, but to a very limited extent and with little success on the upland. The same is true of sweetclover, which, however, does not replace alfalfa or assume equal importance on the bottom or subirrigated lands.

Attempts to grow corn on the upland were continued for many years, but results were so universally unprofitable that corn is seldom planted now on such land, its production being confined to sandy bottom-land fields, where moisture conditions are more favorable. Even under the most favorable conditions the quality of corn is only fair, and the yields fluctuate widely.

Winter barley, although grown occasionally for many years, was not important in crop production until 1919. Thereafter the acreage increased with marked rapidity, and now the crop is recognized as important. Winterkilling has been the limiting factor in the production of this crop three times in the 12 years from 1919 to 1930. Its value as a fall, winter, and spring pasture crop is almost as high as the feed or cash value of the grain produced.

Oats are a dependable feed crop which finds a place in the management and operation of nearly every farm. The new varieties, Fulghum and Kanota, introduced in recent years, are rapidly supplanting the Texas Red variety that previously was grown universally.

Kafir, feterita, and sorgo are grown primarily as feed crops and are relied upon extensively because of their ability to withstand adverse conditions. This does not apply strictly to feterita, which is grown in a small way either for late feed or as a late catch crop.

The acreage of broomcorn varies from year to year according to the market, which is subject to wide fluctuations. This crop is produced most profitably on the sandy soils.

Wheat and cotton are grown extensively and are the principal cash crops. Cotton occupies approximately one-third of the cultivated farm acreage. Probably no other crop is so well suited to the hot, droughty periods as cotton. It has an important place, even on farms that have sound systems of diversification. Hard and soft varieties of winter wheat are grown in about equal proportion. In recent years there has been a decided tendency to increase the acreage of hard wheat. The dividing line between the hard and soft wheat belts of the State extends from north to south through the vicinity of Lawton. The recent development of power farming adapted to wheat, oats, and barley has increased the acreage of these small-grain crops. It is likely, however, that the increased acreage will be confined largely to wheat, which is a cash crop, rather than to oats and barley, which are grown primarily as feed crops.

Cowpeas are grown commonly on both tight soil and sandy soil. The crop is dependable, but returns largest yields when grown on sandy soil. The difficulty of harvesting cowpeas satisfactorily and of curing the hay restricts the acreage to a point where such varieties as may best be used for human consumption are generally grown.

DESCRIPTION OF THE STATION

The experiment station consists of 160 acres of gently rolling upland. Three distinct drainage courses pass through the farm in a southerly direction, making much of it unsuitable for experimental purposes. In general, the land slopes gently to the east, but the breaks in topography give some of the fields a slope in three directions.

The soil is a reddish-brown clay loam having a high clay content with a medium supply of organic matter and of fairly good natural fertility. It is classified[1] as Tishomingo and is representative of an isolated area in the red prairies. The surface soil varies in depth from 6 to 12 inches and is underlain by a compact subsoil of reddish-brown to red clay that resists the penetration of water and plant roots. The surface soil is easily compacted, which favors the rapid run-off of storm water, and its shallowness restricts and limits the water-storage capacity. The natural water-holding capacity of the soil is fairly high, but its lack of depth makes crops largely dependent upon a well-distributed rainfall during the growing season.

Fragmental rocks from 1 to 12 inches in diameter permeate the subsoil without any regular formation and frequently outcrop at the surface. They are derived from several kinds of crystalline rocks, mainly of a granitic nature. Small waterworn gravel and rounded calcareous concretions are usually present in both the surface and the subsoil. This occurrence of rock marks the termination of the low, mountainous foothill region lying about 14 miles to the north and the northwest.

The native vegetation is representative of the section. Bluestem bunch grass (*Andropogon scoparius*) constitutes the chief plant cover. Herbaceous plants and other short grasses are well interspersed. When not overstocked, these grasses support a very satisfactory amount of grazing, and when not grazed they may be profitably cut for hay.

[1] BENNETT, H. H. THE SOILS AND AGRICULTURE OF THE SOUTHERN STATES. 399 p., illus., New York. 1921.

CLIMATIC CONDITIONS

Records of precipitation have been kept at Lawton and its vicinity for the 60 years from 1871 to 1930, except 1883 and 1884. The 58-year average annual precipitation is 30.85 inches. There is an extremely wide fluctuation in the annual precipitation, the lowest on record being about 15 inches and the highest about 59 inches.

During the 14 years from 1917 to 1930, when the experimental work on the station as reported in this bulletin was done, the annual precipitation at the station ranged from 17.28 to 43.65 inches and averaged 29.58 inches. The monthly, seasonal, and annual precipitation during this period and the 58-year monthly averages for Lawton and vicinity are given in Table 1.

TABLE 1.—*Monthly, seasonal, and annual precipitation at the Lawton field station, 1917–1930, compared with the averages for Lawton and vicinity for 58 years*

[Data in inches. T=trace]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Seasonal, April to September	Annual
1917	0.30	0.57	1.74	1.28	4.50	1.01	3.02	2.84	0.72	0.19	1.08	0.03	13.37	17.28
1918	.20	.25	2.16	2.36	1.29	3.08	2.57	1.48	4.18	8.68	1.20	3.50	14.96	30.95
1919	.54	1.41	2.99	4.60	5.44	4.36	3.71	1.98	1.67	13.78	2.25	.92	21.76	43.65
1920	1.04	.61	1.84	3.14	7.53	.69	1.88	4.18	2.05	8.78	2.29	.86	19.47	34.89
1921	1.15	1.47	2.05	2.14	1.30	5.93	2.95	.83	2.13	.03	T	.53	15.28	20.51
1922	.89	.46	.97	6.85	6.63	1.01	3.40	.64	1.61	2.46	1.04	.21	20.14	26.17
1923	4.37	.70	1.30	3.48	5.56	2.68	1.25	1.79	4.99	9.04	3.51	1.76	19.75	40.43
1924	.20	.11	2.47	3.88	3.05	3.36	1.39	4.15	.61	.78	.50	.99	16.44	21.49
1925	.95	.82	T	5.78	2.00	.65	2.01	3.52	7.73	3.58	1.83	.11	21.69	28.98
1926	1.33	0	1.67	2.22	3.79	1.20	2.10	7.48	4.67	4.78	.22	4.50	21.46	33.96
1927	1.45	1.41	2.37	3.22	3.17	2.71	3.44	2.65	4.67	1.71	.72	1.33	19.86	28.85
1928	.59	1.26	1.08	1.90	2.78	8.01	2.28	1.21	.66	2.02	2.67	1.28	16.84	25.74
1929	.94	.80	3.10	.01	12.26	1.94	3.15	.31	4.43	2.30	1.25	.23	22.10	30.72
1930	.82	.19	.26	4.08	5.75	2.47	.57	.55	1.70	9.74	1.64	2.67	15.12	30.44
Average, 14 years	1.06	.72	1.71	3.21	4.65	2.79	2.41	2.40	2.99	4.85	1.44	1.35	18.45	29.58
Average, 58 years	1.08	1.10	1.63	3.03	5.05	3.46	3.06	2.89	3.13	3.01	1.81	1.60	20.62	30.85

The annual precipitation, however, has but little value as an index to the possibilities of crop production. The seasonal distribution of the precipitation, temperatures, humidity, wind velocity, and evaporation are the important climatic factors in this connection. In 1918 the annual precipitation was about normal, but crops were the poorest in the history of the station. In 1924 the precipitation was only 21.49 inches and crops were at the peak of production.

Evaporation was measured by daily readings of the change in the water level of a tank 24 inches deep and 6 feet in diameter sunk in the ground to a depth of 20 inches and kept filled to about the level of the ground. At most stations the evaporation is measured for the six months from April to September, but at Lawton the season is so long that the measurements were continued through November. The monthly evaporation during the months in which it was measured from 1917 to 1930, inclusive, is given in Table 2. For comparison with data from other stations, the totals for the six months from April to September are given, as well as the totals for the eight

months from April to November. The average seasonal evaporation for the six months was 43.482 inches and for the eight months 50.605 inches. Evaporation is highest during July and August, when the humidity is low, temperatures are high, and the rainfall is usually scant.

TABLE 2.—*Average monthly evaporation at the Lawton field station from April to November, inclusive, for the 14 years 1917–1930, with totals for 6-month and 8-month periods*

[Data in inches]

Year	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Total	
									Apr.–Sept.	Apr.–Nov.
1917	8.402	7.310	10.240	10.064	8.514	6.495	7.405	3.602	51.025	62.032
1918	6.138	8.826	7.999	10.528	12.132	6.773	3.796	2.541	52.396	58.733
1919	4.756	5.405	5.357	7.183	8.213	6.103	3.070	2.299	37.017	42.386
1920	7.084	5.088	7.647	7.984	5.236	5.292	3.866	2.242	38.331	44.439
1921	5.205	6.412	5.139	7.045	8.101	6.851	5.746	3.533	38.753	48.032
1922	4.418	4.615	6.533	8.580	8.791	6.626	4.637	2.328	39.563	46.528
1923	4.670	6.492	7.096	8.665	9.952	5.358	3.019	1.799	42.233	47.051
1924	5.190	6.099	9.067	8.056	8.716	6.392	4.775	3.354	43.520	51.649
1925	6.979	6.014	10.364	11.564	7.619	6.152	3.823	2.519	48.692	55.034
1926	4.671	6.353	9.011	8.739	8.242	5.625	3.905	3.469	42.641	50.015
1927	5.061	7.882	7.572	7.886	7.643	6.185	3.930	3.168	42.229	49.327
1928	5.111	6.151	6.324	7.604	7.973	7.521	6.140	2.531	40.684	49.355
1929	5.414	5.834	8.476	8.549	10.269	5.001	4.113	2.154	43.543	49.810
1930	6.254	5.508	7.747	10.466	10.097	8.052	3.388	2.563	48.124	54.075
Average	5.668	6.285	7.755	8.780	8.678	6.316	4.401	2.722	43.482	50.605

Wind velocity was measured by a Robinson 4-cup anemometer exposed at a height of 2 feet above the ground. The average monthly wind velocity for the 14 years from 1917 to 1930 is given in Table 3. The average wind velocity is comparatively low, except in March and April, when an average velocity of 7 or 8 miles an hour may be expected.

TABLE 3.—*Average monthly wind velocity (in miles per hour) measured at 2 feet from the ground at the Lawton field station for the 14 years 1917–1930*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1917	5.8	3.8	10.0	10.8	7.8	7.0	6.2	5.2	4.6	7.7	5.3	6.7
1918	7.8	6.7	6.7	7.9	9.6	4.7	5.8	6.1	5.3	3.9	5.6	5.1
1919	4.4	7.4	6.9	6.7	4.9	3.3	4.0	4.6	5.5	5.9	5.2	5.8
1920	4.9	5.6	8.8	9.0	5.5	5.1	3.8	4.1	4.7	5.7	5.4	5.9
1921	6.4	6.0	7.9	8.1	6.1	4.5	4.3	4.4	5.8	6.1	5.5	6.5
1922	6.4	8.6	9.9	7.8	5.5	3.9	4.8	4.1	3.6	4.2	5.0	5.7
1923	5.4	6.4	9.7	7.6	6.9	5.2	3.3	4.6	4.0	4.4	4.0	6.6
1924	6.2	6.8	7.2	6.2	5.2	6.3	4.6	5.3	4.4	3.7	5.1	5.0
1925	5.7	6.8	8.0	7.5	5.1	5.9	5.5	3.3	3.8	5.0	4.4	5.8
1926	6.6	7.1	7.7	6.8	5.3	5.1	4.2	3.9	4.4	3.8	5.8	6.0
1927	6.3	7.7	8.1	6.7	7.1	4.8	3.7	4.2	5.4	4.5	6.9	6.4
1928	5.9	6.7	7.3	9.0	5.9	6.6	4.1	3.6	4.0	6.4	6.9	6.5
1929	8.2	7.5	8.6	8.0	7.4	6.1	4.1	3.9	3.4	4.0	5.2	4.7
1930	6.6	5.9	7.5	7.4	6.4	6.2	4.3	3.4	4.7	4.8	5.1	5.5
Average	6.2	6.6	8.2	7.8	6.3	5.3	4.5	4.3	4.5	5.0	5.4	5.9

The mean monthly maximum and minimum temperatures for the 14-year period from 1917 to 1930 are given in Table 4.

TABLE 4.—*Mean monthly maximum and minimum temperatures (°F.) at the Lawton field station for the 14 years 1917–1930*

Year	Jan.		Feb.		Mar.		Apr.		May		June		July		Aug.		Sept.		Oct.		Nov.		Dec.	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
1917	54	24	56	26	67	38	74	48	77	52	93	61	97	69	93	67	89	60	75	42	68	39	43	23
1918	41	17	60	30	71	42	70	46	86	62	96	70	97	70	101	71	81	55	75	54	57	41	52	32
1919	49	28	51	30	63	41	70	48	76	57	84	65	91	69	94	69	85	64	70	52	58	35	46	25
1920	46	28	55	32	65	38	71	44	79	59	87	65	93	69	87	65	86	62	76	53	57	35	54	27
1921	55	33	58	30	68	43	71	47	82	59	86	67	92	70	97	70	92	67	80	48	66	33	56	29
1922	47	25	58	29	64	38	71	51	79	59	90	66	96	69	99	70	90	61	77	49	63	40	55	29
1923	62	33	49	29	60	33	73	49	79	57	87	67	97	70	97	69	85	64	65	49	60	39	52	32
1924	47	21	54	29	54	33	71	48	76	52	94	69	92	68	96	71	84	55	80	49	67	38	45	21
1925	47	23	63	30	72	41	80	55	79	57	97	70	98	72	92	68	87	65	65	44	62	35	52	25
1926	47	25	63	32	58	37	67	44	81	57	91	64	93	68	94	68	84	63	76	53	61	33	49	30
1927	50	27	58	35	64	39	76	51	86	61	88	65	92	68	91	67	86	62	80	49	68	41	47	22
1928	54	27	55	31	67	39	70	46	83	57	85	65	92	70	94	68	89	58	81	53	58	38	53	28
1929	48	24	40	23	66	38	78	52	76	56	90	67	93	69	99	69	84	60	75	51	52	32	57	27
1930	33	14	64	35	63	35	82	53	79	57	89	67	97	69	99	69	91	64	69	50	62	37	49	29
Average	49	25	56	30	64	38	73	49	80	57	90	66	94	69	95	69	87	61	75	50	61	37	51	27

The long-time average frost-free period of 214 days provides a long growing season which permits the production of a wide variety of cash and feed crops. Killing frosts in the spring are a source of danger chiefly to fruit and truck crops. Late-maturing cotton is the only crop likely to suffer frost damage in the autumn. The latest killing frost in the spring on record from 1893 to 1930 occurred May 1, 1903, and the earliest killing frost in autumn was on September 26, 1912. Table 5 gives the frost data for the 14-year period from 1917 to 1930. The average frost-free season during this period was 219 days.

TABLE 5.—*Dates of the last killing frost in spring and the first in autumn and the number of frost-free days at the Lawton field station for the 14 years 1917–1930*

Year	Last frost in spring	First frost in autumn	Length of frost-free season (days)	Year	Last frost in spring	First frost in autumn	Length of frost-free season (days)
1917	Apr. 8	Oct. 19	194	1925	Mar. 18	Oct. 27	223
1918	Apr. 9	Nov. 18	223	1926	Apr. 14	Nov. 4	204
1919	Mar. 11	Nov. 10	244	1927	Mar. 19	Nov. 15	241
1920	Apr. 4	Nov. 1	211	1928	Mar. 29	Nov. 3	219
1921	Apr. 17	Nov. 10	207	1929	Mar. 16	Oct. 24	222
1922	Mar. 12	Nov. 13	246	1930	Mar. 30	Oct. 31	215
1923	Apr. 5	Nov. 5	214				
1924	Mar. 31	Oct. 23	206	Average	Mar. 29	Nov. 3	219

ROTATION AND TILLAGE EXPERIMENTS

Crop rotation and tillage experiments are conducted on 0.1-acre plots. The crops grown are winter wheat, oats, winter barley, spring barley, rye, cotton, peanuts, cowpeas, alfalfa, sweetclover, corn, kafir, sorgo, feterita, and broomcorn. The rotations are from two to six years in length, but the greater part of the work is with 2-year and 3-year rotations. Experiments in continuous cropping and methods of tillage include cotton, broomcorn, corn, sorgo, kafir,

feterita, and winter wheat. These experiments are carried on in two separate fields, known as field A and field B.

All the experiments in which there are grain sorghums, forage sorghums, and corn are in field A, and all in which there are small-grain crops, except oats, are in field B. This arrangement was made necessary because of the severe damage to the row crops from the chinch bug. When feed and forage crops are grown adjacent to wheat or barley, the chinch bug has proved to be the largest single menace or hazard to experimental production and was responsible for low yields and failures when climatic conditions were favorable to average or better yields. The damage by the insect is responsible for breaks in the continuity of many experiments, made because it became necessary to revise rotations and place them in new locations. These adjustments were resorted to only after several years of attempting to combat the damage and to protect the continuity of the work begun in 1916.

It is readily recognized that the risk and danger involved in protecting and producing a crop yield from a small area, such as an experimental plot that is directly exposed to a heavy migration and concentration of chinch bugs, is much greater than on the average farm field, where a small loss may be sustained while measures designed to reduce the infestation are being established. The chinch bugs have well-known and decided crop preferences, and their behavior during the season as various crops mature may be pretty definitely anticipated. It has become a well-established practice to separate small grain crops as widely as possible from row crops of grain sorghums, forage sorghums, and corn. In the organization and establishment of cropping systems and rotations the hazard of destructive crop insects becomes a factor equal in importance to that of soil and climate.

During the years in which experiments in crop production have been conducted at Lawton, conditions that influence crop yields have presented extreme variations.

A combination of crop rotations and tillage methods with different crops provides a number of comparisons between spring plowing and fall plowing, listing, and disking.

Fall plowing is done as soon as practicable after the crop is removed. However, the nature of the crop previously grown may extend this operation over a rather long period. After corn such plowing may be done in October, but after cotton the same operation is not generally possible until December and often later, when it might well be termed winter plowing.

The preparation of land for small grain after wheat, oats, and barley has considerable latitude in time. These crops are usually harvested in the latter part of May and in early June, but seeding of wheat and winter barley may be done as early as September 1 and as late as December 1, although the practicability of late seeding is questionable. Oats, on the other hand, are generally seeded early in February; sometimes sooner, if the weather permits.

RESULTS WITH CORN

Although the impracticability of growing corn on the tight upland soils of southwestern Oklahoma is definitely recognized, a limited amount of experimental work on methods of tillage and crop se-

quence has been done. The results are presented in Table 6. In the continuous record of corn production for the 14-year period 1917 to 1930, three entire failures of grain were recorded and four years of low yields, when the quality of the grain produced was scarcely marketable. The wide fluctuations in annual yields from total failures in 1917, 1918, and 1925, to an average yield of 36.7 bushels to the acre in 1919, emphasize the uncertainty of production. The 14-year average yield under each method is so low that the slight advantage of one over the other has but little significance. The quality of the grain, with but few exceptions, was very inferior.

A slight increase in the production of both grain and stover when corn is grown continuously resulted from subsoiling, but this method is too expensive to justify the extra labor involved. Barnyard manure applied as a top-dressing on spring-plowed land gave a greater increase in the yield of stover than in the yield of grain.

Corn on spring-plowed oat land produced the lowest average yield for the 14-year period. This method of production is involved in a 6-year rotation originally arranged as follows: Oats, corn, wheat, and three years of alfalfa. Beginning with the crop year of 1922, wheat was replaced by cotton. This rotation is so located in field A that the corn has always been subject to heavy damage from chinch bugs that migrate from near-by areas of native grass.

The 14-year averages from 1917 to 1930, inclusive, are somewhat lower than those of the six years from 1917 to 1922, but the relative performances of the different methods of tillage and crop sequence are practically the same for the two periods.

With respect to the results presented for only the six years from 1917 to 1922, it should be explained that where corn follows milo the milo was the second crop in a single year, being planted on wheat stubble as soon as possible after harvest. Cowpeas and rye used as green-manure crops for corn were sown after winter wheat was harvested.

Milo grown in this manner produced but two yields of grain in the six years—2.9 and 11.7 bushels to the acre in 1917 and 1920, respectively. Corn and milo were so frequently damaged by chinch bugs that the results do not warrant detailed analysis and study. There is some possibility of growing a second crop in a single year when moisture conditions are unusually favorable, but the extent to which this practice may be followed is governed by rainfall and the presence of destructive crop insects, and its advisability depends upon the demand for feed and the subsequent effect on the crop to be grown the following year.

Regardless of the quantity of water stored in the soil, temperature, humidity, wind movement, and insects constitute hazards during the period of growth and development of the corn crop that usually eliminate most of the advantages that might have been obtained from a well designed and executed method of tillage. Nevertheless, as a sound farm principle and intelligent practice, tillage designed to eliminate weed growth should accompany the attempted production of corn.

TABLE 6.—*Acre yields of corn grown by different methods at the Lawton field station, 1917–1930*

GRAIN (bushels)

Previous crop and treatment	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average 1917–1930	Average 1917–1922
Corn:																
Spring plowed	0	0	42.7	21.5	32.2	11.3	11.1	14.7	0	7.1	22.0	16.8	25.1	2.3	14.8	18.0
Spring plowed, top-dressed	0	0	43.3	21.6	45.0	22.9	10.5	20.3	0	10.9	28.3	26.0	38.0	14.8	20.1	22.1
Fall plowed	0	0	40.1	24.1	28.8	12.6	13.7	14.5	0	6.3	23.6	18.3	25.9	2.5	15.0	17.6
Fall plowed, subsoiled	0	0	49.2	29.5	40.7	17.9	15.1	19.5	0	12.1	26.5	25.1	27.2	8.3	19.4	22.9
Listed	0	0	35.1	25.8	32.5	11.6	7.3	17.0	0	11.3	13.3	20.2	26.6	11.0	15.1	17.5
Oats:																
Spring plowed	0	0	32.9	18.3	29.3	12.3	5.2	16.0	0	0	18.9	13.7	26.8	2.1	12.5	15.5
Fallowed	0	0	49.5	24.9	46.7	16.9	16.9	19.1	0	16.5	24.8	24.7	29.6	8.7	19.9	23.0
Sorgo:																
Fall plowed							14.5	13.2	0	0	26.1	16.4	26.4	0	[1] 12.1	
Wheat and milo:																
Spring plowed	0	0	31.6	14.3	28.5	5.0										13.2
Wheat:																
Spring plowed	0	0	30.0	18.9	25.4	7.0										13.6
Spring plowed, manured	0	0	30.7	23.6	38.8	4.7										16.3
Wheat, cowpeas:																
Green manured	0	0	32.3	14.7	27.6	2.7										12.9
Wheat, rye:																
Green manured	0	0	22.7	12.1	19.6	3.1										9.6

STOVER (pounds)

Corn:																
Spring plowed	2,050	1,700	3,700	2,300	3,000	1,650	1,900	1,300	650	1,300	1,250	1,350	1,400	1,080	1,759	2,400
Spring plowed, top-dressed	2,950	2,350	5,100	4,100	4,850	3,100	1,600	2,000	1,350	1,350	2,060	2,300	2,900	1,340	2,664	3,742
Fall plowed	2,300	1,750	3,550	2,450	2,800	1,500	1,900	1,500	800	1,150	1,300	1,350	1,450	1,260	1,790	2,392
Fall plowed, subsoiled	2,650	3,400	3,850	2,750	3,700	1,900	2,200	2,000	1,050	1,500	1,250	1,850	1,650	1,130	2,206	3,042
Listed	2,175	2,200	2,525	2,325	2,525	1,925	1,875	1,600	750	1,250	950	1,400	1,350	930	1,699	2,279
Oats:																
Spring plowed	2,000	1,550	2,530	3,180	3,400	1,850	1,950	1,550	750	1,400	1,500	1,850	2,150	1,490	1,939	2,418
Fallowed	2,450	1,750	3,700	2,300	3,700	1,800	2,550	1,750	1,250	1,500	1,350	1,950	2,100	700	2,061	2,617
Sorgo:																
Fall plowed							2,100	1,550	350	2,050	1,550	1,850	1,950	300	[1] 1,463	
Wheat and milo:																
Spring plowed	1,400	900	1,980	2,680	2,500	1,950										1,902
Wheat:																
Spring plowed	1,250	1,300	2,100	2,980	2,700	1,850										2,030
Spring plowed, manured	2,750	2,030	2,650	3,680	3,750	2,300										2,860
Wheat, cowpeas:																
Green manured	1,100	920	2,080	2,850	2,800	1,650										1,900
Wheat, rye:																
Green manured	1,150	880	2,400	2,590	2,850	1,850										1,953

[1] 8-year average.

129789°—32——2

RESULTS WITH KAFIR

The results of the crop-rotation and cultivation work with kafir from 1917 to 1930, inclusive, are shown in Tables 7 and 8 and in Figure 1. During the 14 years complete failures of grain from this crop were recorded twice—in 1918 and in 1930. Entire failures of both grain and stover occurred on individual plots in several other seasons. These failures were the results of chinch-bug damage rather than of cultural practices. The wide fluctuation of annual yields and the comparatively small difference in average yields between kafir and corn would indicate that the production of kafir was almost as uncertain as that of corn. However, the crop occupies an important place in the production of feed for individual farm use and is definitely recognized as being more dependable and more productive than corn, especially in the drier years. It is generally necessary to plant corn as early in the spring as possible, usually the latter part

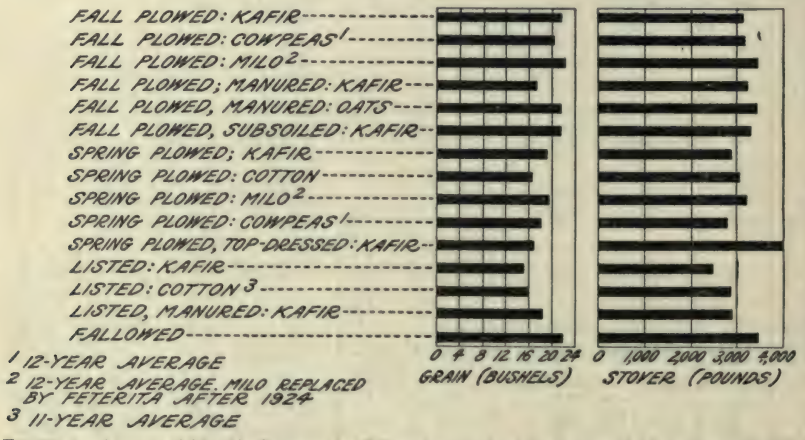


FIGURE 1.—Average yields of kafir grown by different methods at the Lawton field station, 1917–1930

of March or early April. Kafir, however, may be planted from the first part of April to the middle of June, the time depending entirely on climatic and soil conditions. Although the yields may frequently be low, the quality of the grain is almost always superior to that of corn. The yield of kafir stover, which finds a wide use as roughage for livestock, has exceeded the yield of corn stover in comparable tests (Table 12) by an average of 1,288 pounds to the acre.

Fall plowing for kafir increased the yield less than 3 bushels to the acre over spring plowing, irrespective of the preceding crop. In continuous cropping, subsoiling had no influence on the average yield of grain and increased the yield of stover only 116 pounds. The milo that preceded kafir in the rotations made but little plant growth, being destroyed early in the season by chinch bugs. In the attempt to produce milo during the seven years from 1917 to 1923, yields were obtained only three times. Feterita was substituted for milo beginning with the crop of 1924, and became the previous crop instead of milo beginning with 1925. Land previously cropped to cowpeas which were harvested as hay during the 12 years from 1919 to 1930 averaged 2.2 bushels more when fall plowed than it did when spring

plowed. Kafir did not yield as heavily on either fall plowing or spring plowing following cowpeas as it did following kafir.

Kafir on spring-plowed cotton land yielded an average of 2.6 bushels to the acre less than on land continuously spring plowed and cropped to kafir for the 14-year period. The former method proved to be one of the poorest tested.

Kafir, continuously cropped on land that was fall plowed and manured, yielded 4.3 bushels of grain to the acre less than kafir grown by the same method without manure. When manure was applied as a top-dressing on spring-plowed land continuously cropped, the yield of grain was reduced 2 bushels to the acre and the yield of stover increased about 1,200 pounds to the acre as compared with the yield under similar treatment without manure. Fall-plowed oat stubble to which manure was applied gave good yields of both grain and stover, but there was no corresponding treatment without manure.

The reduction in grain yields from the use of manure may be due to several factors. It has been observed that the plants were stimulated to a more rapid succulent growth by the manure. This depleted the soil moisture rapidly and frequently caused the crop to suffer from drought early in the season. The grain was advanced in maturity over surrounding crops, and became subject to bird damage that was difficult to control, especially on small areas.

Manure on continuous cropping was applied annually at the rate of approximately 3 tons to the acre. On the fall-plowed oat land, where the kafir was grown in a 4-year rotation, the manure was applied at the rate of 10 tons to the acre.

As a method of seed-bed preparation for kafir, listing produced lower yields than either spring plowing or fall plowing during the 14 years that it was tested.

In the continuous-cropping series of kafir plots, A is spring plowed, B is fall plowed, and F and G are spring listed. From 1917 to 1920, inclusive, plot F was lister planted without any previous treatment, and plot G was disked in the spring and lister planted at seeding time. Beginning with 1921, both plots were disked in the spring, plot F was shallow listed, and plot G was deep listed at planting time. The 14-year average acre yields of these plots from 1917 to 1930 were A, 19.3 bushels; B, 22.3 bushels; F, 14.1 bushels; and G, 14.8 bushels. The average of plots F and G listed is 6.3 bushels less than the average of plots A and B plowed. The 11-year (1920–1930) average acre yield of kafir continuously cropped on listed land is 0.5 of a bushel less than on listed cotton land. Where manure was applied to kafir continuously cropped on listed land, the 14-year average acre yield was 18.7 bushels, which was 3.8 bushels more than on land with the same treatment without manure. (Table 7.)

The application of manure to kafir on listed land has resulted in a slight increase in grain yields and a decrease in stover yields in comparison with similar applications on either spring-plowed or fall-plowed land.

The problem of securing good, uniform stands on listed land is important. Germination and subsequent growth for a few weeks are slower on listed land than on plowed land that has been surface planted. The probability of stands being reduced by heavy rains when listing is practiced is also greater, and frequently replanting is necessary.

TABLE 7.—*Acre yields of kafir grown by different methods at the Lawton field station, 1917–1930*

GRAIN (bushels)

Treatment and previous crop	Number of plots averaged	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
Fall plowed:																
Kafir	2	19.3	0	31.4	36.2	28.7	3.4	17.1	35.6	11.2	26.8	30.2	34.5	27.8	0	21.6
Cowpeas	1			35.8	34.8	27.5	4.0	12.8	31.0	11.5	13.3	17.5	33.3	24.3	0	[1] 20.5
Milo [2]	2			34.7	42.6	27.3	3.3	14.5	31.0	12.2	24.4	16.1	37.4	20.5	0	[1] 22.0
Average		19.3	0	34.0	37.9	27.8	3.6	14.8	32.5	11.6	21.5	21.3	35.1	24.2	0	20.3
Fall plowed, manured:																
Kafir	1	19.5	0	25.8	34.3	29.3	0	0	28.7	7.7	16.8	33.3	24.0	23.0	0	17.3
Oats	1	16.7	0	43.2	36.8	37.0	0	15.0	37.3	10.8	14.2	37.5	34.3	22.7	0	21.8
Average		18.1	0	34.5	35.6	33.2	0	7.5	33.0	9.3	15.5	35.4	29.2	22.9	0	19.6
Fall plowed, subsoiled:																
Kafir	1	14.5	0	30.7	40.8	29.2	6.2	16.3	33.7	13.0	25.5	27.8	38.8	26.8	0	21.7
Spring plowed:																
Kafir	2	15.5	0	28.8	36.7	24.5	7.2	15.1	28.3	9.5	22.3	21.3	34.4	20.4	0	18.9
Cotton	3	2.3	0	30.3	41.2	24.6	1.2	1.7	31.2	2.7	18.3	15.2	30.2	28.8	0	16.3
Milo [2]	1			27.8	45.2	21.2	7.8	12.5	25.7	10.7	21.8	14.2	25.8	19.5	0	[1] 19.4
Cowpeas	4			29.0	37.8	24.1	1.5	7.5	28.9	15.6	15.7	9.8	30.1	20.1	0	[1] 18.3
Average		8.9	0	29.0	40.2	23.6	4.4	9.2	28.5	9.6	19.5	15.1	30.1	22.2	0	17.2
Spring plowed, top-dressed:																
Kafir	1	12.3	0	7.7	34.0	8.3	5.2	13.2	30.7	15.2	22.2	28.7	33.0	26.7	0	16.9
Listed:																
Kafir	9	13.2	0	24.1	27.3	18.4	1.4	5.5	23.5	13.4	22.4	17.3	24.4	17.2	0	14.9
Cotton	1				32.4	19.2	0	0	30.5	5.7	12.2	28.0	28.3	18.8	0	[3] 15.9
Average		13.2	0	24.1	29.9	18.8	.7	2.8	27.0	9.6	17.3	22.7	26.4	18.0	0	15.0
Listed, manured:																
Kafir	1	17.8	0	25.8	22.5	30.7	2.7	11.0	31.0	15.0	25.8	21.3	29.3	29.2	0	18.7
Fallowed	3	18.7	0	31.1	39.3	28.0	3.2	16.8	33.5	18.8	27.1	21.6	42.9	27.8	0	22.1
Average		18.3	0	28.5	30.9	29.4	3.0	13.9	32.3	16.9	26.5	21.5	36.1	28.5	0	20.4

STOVER (pounds)

Fall plowed:																
Kafir	2	4,970	1,350	4,245	4,255	3,780	1,696	2,335	5,240	1,530	2,720	3,045	3,650	3,655	1,450	3,137
Cowpeas	1			4,700	3,490	3,500	3,440	1,430	4,790	1,760	3,250	1,760	3,950	3,690	2,050	[1] 3,151
Milo [2]	2			4,970	4,945	3,440	4,270	1,855	4,720	2,520	3,550	1,730	4,335	2,895	1,750	[1] 3,420
Average		4,970	1,350	4,638	4,230	3,573	3,135	1,873	4,917	1,937	3,173	2,178	3,998	3,413	1,750	3,224
Fall plowed, manured:																
Kafir	1	5,310	1,100	4,000	4,040	4,090	0	2,150	5,130	1,390	3,540	3,900	5,280	3,820	2,250	3,286
Oats	1	5,420	2,250	5,010	5,040	5,030	0	1,900	5,960	2,500	3,350	2,830	4,290	2,090	1,700	3,384
Average		5,365	1,675	4,505	4,540	4,560	0	2,025	5,545	1,945	3,445	3,365	4,785	2,955	1,975	3,335
Fall plowed, subsoiled:																
Kafir	1	5,020	1,150	4,760	4,600	3,450	3,330	1,870	5,380	1,670	2,570	2,730	4,070	3,190	1,750	3,253
Spring plowed:																
Kafir	2	4,810	1,350	3,670	4,150	2,480	2,820	1,845	4,405	1,280	2,825	2,310	3,615	3,300	1,450	2,879
Cotton	3	2,965	1,375	4,435	5,103	3,937	2,697	2,267	5,093	1,003	3,477	1,693	3,837	3,390	983	3,018
Milo [2]	1			4,030	3,540	2,830	3,730	1,440	4,060	1,660	6,170	1,400	6,100	2,830	600	[1] 3,199
Cowpeas	4			4,210	3,958	2,903	813	1,550	4,520	2,415	2,985	1,140	3,895	3,695	1,600	[1] 2,807
Average		3,888	1,363	4,086	4,188	3,038	2,515	1,776	4,520	1,590	3,864	1,636	4,362	3,304	1,158	2,949
Spring plowed, top-dressed:																
Kafir	1	4,870	1,900	4,540	4,400	5,600	3,890	2,460	5,160	3,140	3,520	3,780	7,320	3,800	2,750	4,081
Listed:																
Kafir	9	3,436	906	3,063	3,349	2,606	752	2,413	3,796	1,991	2,453	1,958	2,936	3,202	1,528	2,456
Cotton	1				3,445	2,400	2,150	2,000	4,770	1,110	2,820	2,920	4,100	3,220	2,450	[3] 2,853
Average		3,436	906	3,063	3,397	2,503	1,451	2,207	4,283	1,551	2,637	2,439	3,518	3,211	1,989	2,614
Listed, manured:																
Kafir	1	4,520	700	3,200	4,000	3,810	1,090	2,540	4,290	2,250	2,650	3,070	3,340	3,200	2,250	2,922
Fallowed	3	5,310	3,100	4,285	4,440	3,607	1,110	1,940	4,615	2,845	3,255	2,425	4,675	3,810	2,175	3,399

[1] 12-year average.

[2] Milo replaced by feterita beginning with 1925.

[3] 11-year average.

TABLE 8.—*Acre yields of kafir continuously cropped on different methods of listing at the Lawton field station, 1917–1930*

GRAIN (bushels)

Plot	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
A	12.7	0	24.7	28.3	17.9	0	7.5	24.7	14.8	23.3	17.5	27.3	15.8	0	15.3
B	14.0	0	22.3	27.5	22.5	0	5.5	22.2	12.7	23.3	17.3	24.7	17.5	0	15.0
C	12.2	0	24.2	24.3	17.5	0	6.2	20.7	14.7	21.3	12.7	25.7	15.0	0	13.9
D	14.0	0	24.3	23.2	15.8	0	7.8	22.2	9.3	22.2	9.5	20.7	12.0	0	12.9
E	16.5	0	30.5	32.3	16.8	0	10.2	25.2	14.2	24.3	19.2	24.0	12.3	0	16.1
F	16.0	0	28.5	29.7	22.7	2.3	5.7	23.2	13.0	21.3	16.5	26.8	12.0	0	15.6
G	16.5	0	29.8	26.5	21.7	2.0	7.0	24.7	11.8	22.5	14.3	28.7	20.3	0	16.1
H	17.8	0	25.8	22.5	30.7	2.7	11.0	31.0	15.0	25.8	21.3	29.3	29.2	0	18.7
Average	15.0	0	26.3	26.8	20.7	.9	7.6	24.2	13.2	23.0	16.0	25.9	16.8	0	15.5

STOVER (pounds)

A	4,070	800	2,970	3,000	2,550	0	2,400	3,720	2,210	2,760	1,700	3,160	2,800	1,550	2,406
B	3,500	900	2,710	2,700	2,900	0	2,020	3,570	1,990	2,540	1,760	2,720	2,900	1,700	2,279
C	2,790	750	2,800	3,040	2,450	0	2,180	3,360	1,970	2,350	1,490	2,760	2,650	1,350	2,139
D	3,410	800	3,040	3,060	2,175	0	1,980	3,520	1,390	2,630	1,630	2,510	2,380	1,350	2,134
E	3,170	1,050	3,620	3,710	2,690	0	2,450	4,090	1,950	2,240	2,050	2,810	3,710	1,700	2,517
F	4,430	700	3,240	3,020	2,690	860	2,110	3,910	1,970	2,620	1,810	3,140	3,330	1,650	2,534
G	3,980	1,000	3,560	4,110	2,825	380	2,180	3,720	1,790	2,650	1,740	3,280	3,480	1,650	2,596
H	4,520	700	3,200	4,000	3,810	1,090	2,540	4,290	2,250	2,650	3,070	3,340	3,200	2,250	2,922
Average	3,734	838	3,143	3,330	2,761	291	2,233	3,773	1,940	2,555	1,906	2,965	3,056	1,650	2,441

Summer fallow did not show any advantage in the production of kafir during the 14 years that it was tested.

The average yields of kafir under different methods of tillage and crop sequence during the 14 years from 1917 to 1930 are shown graphically in Figure 1.

In Table 8 are shown the results with kafir grown under eight different methods of listing for the 14 years from 1917 to 1930. The methods employed on the eight plots were as follows:

Plot A.—Fall disk, winter list, level in spring, lister plant in same furrows.
Plot B.—Fall list, level in winter, lister plant in same furrows.
Plot C.—Fall list, level in spring, lister plant in same furrows.
Plot D.—Fall list, harrow in the spring, plant by splitting the ridges.
Plot E.—Fall list, plant by splitting the ridges.
Plot F.—Early spring list, cultivate to keep clean until planting time, plant in the same furrows.
Plot G.—Early spring list, plant by splitting the ridges.
Plot H.—Fall disk, manure, winter list, level in the spring, lister plant in the same furrows.

The spread in the 14-year averages, excepting plot H, is not wide, averaging only 3.2 bushels to the acre between plot D and plots E and G. The highest average acre yield obtained for the 14-year period was 18.7 bushels on plot H where manure was applied. Plot D produced the lowest average yield, 12.9 bushels to the acre.

Chinch bugs have always been a damaging factor in this experiment, and if it were possible to eliminate that factor completely the results might well be subject to an entirely different interpretation. This statement applies as well to any experiment that includes kafir in a rotation or any other system of cropping.

RESULTS WITH SORGO

Sorgo has been grown in rows continuously for a period of 14 years on a series of plots under different methods of tillage. Sumac, which is a dependable variety, has been used throughout the test. Chinch bugs frequently inflict serious damage, and after a few years' experience it seemed expedient to plant the crop as early in the spring as practicable. By doing so it is often possible to get the growing crop into a well-advanced, vigorous condition before a heavy infestation of chinch bugs. Planting is usually done from about April 15 to early in May. When the growing plants are approximately 6 inches in height they are uniformly thinned by hand to 6 inches apart in the row.

TABLE 9.—*Acre yields of sorgo grown by different methods at the Lawton field station, 1917–1930*

GRAIN (bushels)

Treatment	Previous crop	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
Spring plowed	Sorgo	15.7	0	29.8	24.3	22.0	[1] 0.0	7.7	15.4	2.0	13.9	15.4	20.0	18.2	0	13.2
Spring plowed, top-dressed	do	17.3	0	32.3	47.0	41.1	3.6	9.1	24.5	15.4	13.8	41.3	33.2	38.8	0	22.7
Fall plowed	do	16.8	0	27.0	24.5	29.1	[1] 0	8.9	15.2	6.4	14.3	26.4	18.9	19.1	0	14.8
Fall plowed, subsoiled	do	16.3	0	32.5	27.0	28.9	5.9	7.3	17.5	6.4	16.1	18.2	31.4	25.7	0	16.7
Listed [2]	do	7.1	0	23.2	31.3	12.9	4.6	5.4	16.1	11.3	20.4	18.2	23.4	15.0	0	13.5
Disked, listed [3]	do	21.3	0	32.9	32.0	24.1	3.0	6.8	17.5	11.6	22.3	15.2	25.7	13.4	0	16.1
Average of listing		14.2	0	28.1	31.7	18.5	3.8	6.1	16.8	11.5	21.4	16.7	24.6	14.2	0	14.8
Fallowed		18.9	0	36.4	24.6	28.9	[1] 0	8.4	17.1	14.6	18.4	26.4	31.6	29.1	0	18.2

STOVER (pounds)

Treatment	Previous crop	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
Spring plowed	Sorgo	8,190	1,150	9,080	10,140	4,820	[1] 0	4,220	7,340	1,590	5,870	2,740	6,880	4,030	1,500	4,825
Spring plowed, top-dressed	do	11,280	1,050	10,540	15,820	7,050	11,860	4,490	10,130	4,040	6,980	7,640	9,540	7,630	4,300	8,025
Fall plowed	do	8,620	900	8,890	10,080	5,770	[1] 0	4,300	7,050	1,540	5,850	4,880	6,190	4,130	1,450	4,975
Fall plowed, subsoiled	do	8,060	730	8,930	10,990	5,780	5,000	3,590	7,320	2,340	6,050	3,130	5,740	7,560	2,250	5,534
Listed [2]	do	5,950	1,550	6,650	7,900	2,580	5,540	3,050	5,250	2,820	6,160	3,330	9,240	5,860	2,450	4,881
Disked, listed [3]	do	8,580	1,050	8,260	9,510	5,300	5,680	3,870	5,170	2,500	6,150	2,700	7,710	7,800	2,750	5,502
Average of listing		7,265	1,300	7,455	8,705	3,940	5,610	3,460	5,210	2,660	6,155	3,015	8,475	6,830	2,600	5,191
Fallowed		8,610	5,200	9,910	9,020	5,680	[1] 0	4,130	7,940	3,580	6,670	4,880	9,180	8,170	2,900	6,134

[1] Failure due to chinch bugs. [2] Beginning with 1921 the land was disked and listed deep. [3] Beginning with 1921 the land was disked and listed shallow

The results of the experiment are given in Table 9. There is little difference in the yields on spring plowing and on fall plowing, but where spring plowing was top-dressed with manure the average grain yield was 8.7 bushels to the acre more than the average of spring plowing and fall plowing without manure. The yield of stover was likewise increased 3,125 pounds to the acre.

Subsoiling did not show any appreciable effect.

The treatment of the two listed plots, F and G, was the same as has been described for similarly designated plots of kafir. From 1917 to 1920, inclusive, the yearly yields of grain were less on plot F than on plot G, except in 1918, when failures were recorded on both plots. The yearly production of stover was likewise less on plot F with one exception. For the 10-year period 1921 to 1930 the average yield of grain on plot G was only 1.3 bushels to the acre more than on plot F. The average yields of stover on these two plots for the same period differ by only 335 pounds to the acre in favor of plot G. The 14-year average of both methods of listing differs but little from the average of spring plowing and fall plowing. The largest average yield of stover for the 14 years, produced on plot G, was 677 pounds to the acre more than the lowest average yield, produced on spring plowing. On summer-fallowed land the yield of grain was 4.5 bushels and of stover 1,891 pounds to the acre less than on continuously cropped land that was spring plowed and top-dressed with manure.

Sorgo has proved to be a dependable crop, and may be relied upon to produce satisfactory yields of forage as roughage for livestock.

RESULTS WITH FETERITA

Feterita is a catch crop that may be sown early in the spring for early feed, or may be sown late in the season as soil-moisture conditions warrant and the feed requirements demand. The crop is more susceptible to injury by chinch bugs than either kafir or sorgo, and its chances of normal growth and development are uncertain. The introduction of Spur feterita in recent years has been of considerable benefit because it is more resistant to chinch-bug damage than is common feterita.

As shown in Table 10, the results of three methods of production for 14 years are available. The difference in average yields between spring plowing and fall plowing continuously cropped to feterita amounted to 2.2 bushels to the acre in favor of fall plowing. Summer-fallowed land proved of no advantage to the production of the crop.

Beginning with 1924, feterita was substituted for milo in a number of rotations, and from then on data from six additional methods are available. In these rotations fall plowing was 2.9 bushels to the acre more productive than spring plowing. There was but little difference in the yields following kafir, cotton, or cowpeas on the spring plowing. On fall plowing, where feterita followed kafir and cowpeas, the difference in yields was also negligible, but in both instances the yields exceed those on spring plowing under the same crop sequence. A still further increase in yield followed when cowpeas were plowed under for green manure instead of being harvested for hay.

TABLE 10.—*Acre yields of feterita grown by different methods at the Lawton field station, 1917–1930*

GRAIN (bushels)

Treatment and previous crop	Plots averaged	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average 1917–1930	Average 1924–1930
Spring plowed:																	
Feterita	1	21.4	0	28.1	21.4	5.2	0	7.6	25.3	2.9	18.1	21.4	22.9	17.9	2.8	13.9	15.9
Kafir	1								20.7	4.3	12.8	14.8	26.9	21.0	3.3		14.8
Cowpeas	1								22.8	8.3	12.9	0	21.0	24.7	3.1		13.3
Cotton	1								23.3	5.9	9.1	6.6	17.9	28.6	0		13.1
Fall plowed:																	
Feterita	1	25.2	0	29.8	26.2	13.1	0	10.3	26.9	5.3	20.5	25.0	19.7	20.0	4.0	16.1	17.3
Kafir	2								24.5	4.7	16.0	9.6	26.4	27.7	5.4		16.3
Cowpeas	1								23.6	13.6	12.8	4.3	25.9	30.2	8.1		16.9
Fallowed	1	22.6	0	33.6	20.7	7.9	0	11.4	24.6	10.8	17.0	12.8	29.8	26.1	5.7	15.9	18.1
Green manured:																	
Cowpeas	1								29.8	6.2	19.1	21.7	36.4	31.4	6.0		21.5

STOVER (pounds)

Treatment and previous crop	Plots averaged	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average 1917–1930	Average 1924–1930
Spring plowed:																	
Feterita	1	2,760	1,700	3,620	3,110	1,300	0	1,360	2,630	430	1,300	2,410	4,170	3,210	440	2,031	2,084
Kafir	1								3,100	750	1,360	1,790	4,990	4,080	960		2,433
Cowpeas	1								2,580	1,170	1,900	0	4,030	3,670	270		1,946
Cotton	1								2,700	1,060	1,120	3,700	3,960	4,540	1,050		2,590
Fall plowed:																	
Feterita	1	4,570	1,500	4,670	3,080	2,490	0	1,900	2,940	390	1,460	2,460	4,310	4,440	520	2,481	2,360
Kafir	2								2,755	830	1,675	970	5,220	4,120	1,115		2,384
Cowpeas	1								2,680	2,210	1,860	600	4,950	4,750	1,680		2,676
Fallowed	1	3,710	2,050	3,450	2,950	2,190	0	1,340	2,915	1,700	1,690	1,410	5,300	3,985	1,195	2,420	2,599
Green manured:																	
Cowpeas	1								2,870	890	1,840	2,150	6,090	3,980	950		2,681

RESULTS WITH MILO

Milo was grown from 1917 to 1923, inclusive. During this 7-year period grain was produced by all methods in three years only, 1917, 1919, and 1920. As shown in Table 11, creditable yields were produced in only two of these years. Total failures were recorded in three of the remaining years of the period and on all but one plot in a fourth year. Of all the grain sorghums, milo is the most susceptible to the chinch bug. In southwestern Oklahoma this insect is the chief inhibiting factor in the production of the crop. This fact is widely recognized, and the acreage devoted to milo is negligible. West and northwest of Lawton, especially near the Oklahoma-Texas line, the acreage and production become considerable.

TABLE 11.—*Acre yields (in bushels) of milo grown by different methods at the Lawton field station, 1917–1923*

Previous crop and treatment	1917	1918	1919	1920	1921	1922	1923	Average
Milo:								
Spring plowed	10.9	0	46.6	31.2	0	0	0	12.7
Spring plowed, top-dressed	9.7	0	48.6	27.1	26.6	0	0	16.0
Fall plowed	8.8	0	50.5	35.9	0	0	0	13.6
Fall plowed, subsoiled	12.6	0	48.6	28.3	0	0	0	12.8
Listed	12.4	0	34.9	16.8	0	0	0	9.2
Cowpeas:								
Green manured	1.0	0	50.5	42.1	0	0	0	13.4
Fallowed	13.6	0	55.3	30.9	0	0	0	14.3

RESULTS WITH CORN, KAFIR, SORGO, AND FETERITA UNDER CONTINUOUS CROPPING

The discussion thus far has involved only such crops as are grown primarily for local consumption, and all rotations and cultural methods used have been included. The results with corn, kafir, sorgo, and feterita, grown for a 14-year period under a system of continuous cropping by different methods of tillage, are summarized in Table 12 and Figure 2. Although there is but little difference between the grain yields of corn and kafir, the quality of the corn was almost always inferior to that of kafir, and the shelling percentage of the corn usually was low. The likelihood of producing at least some grain is also greater with kafir than with corn. Sorgo ranks third in comparison with corn and kafir in the quantity of grain produced and first of all four crops in the production of forage, which constitutes its chief value. In total crop yield sorgo averaged 2,209 pounds per acre more than kafir, 3,407 pounds more than corn, and 2,953 pounds more than feterita grown under comparable methods. Feterita averaged higher in grain production than sorgo and higher in total crop than corn for the three comparable methods of production.

TABLE 12.—*Average acre yields (in pounds) of corn, kafir, sorgo, and feterita on fallow and continuously cropped by different methods of seed-bed preparation at the Lawton field station, 1917–1930*

Tillage	Grain				Total crop			
	Corn	Kafir	Sorgo	Feterita	Corn	Kafir	Sorgo	Feterita
Spring plowed	1,096	1,159	737	808	2,855	3,969	5,562	2,839
Spring plowed, top-dressed	1,491	1,016	1,269	.....	4,154	5,097	9,294	.....
Fall plowed	1,116	1,336	826	936	2,906	4,542	5,801	3,417
Fall plowed, subsoiled	1,436	1,300	933	.....	3,642	4,553	6,466	.....
Listed	1,121	866	829	.....	2,820	3,616	6,020	.....
Fallowed	1,474	1,514	1,040	964	3,534	5,323	7,210	3,459
Average	1,289	1,199	939	903	3,319	4,517	6,726	3,238

The total crop produced was somewhat higher on fall plowing than on spring plowing for all crops. Listing proved to be the poorest method of seed-bed preparation for corn and kafir, but it was slightly better for sorgo than either spring plowing or fall plowing. The gain, however, was too small to be of much significance.

Subsoiling as compared with fall plowing showed a small gain for corn in both grain and total quantity of crop. The difference in yields between the two methods for kafir was negligible. Although subsoiling for sorgo showed an increase of 665 pounds of total crop and 107 pounds of grain to the acre over fall plowing, the difference was not great enough to compensate for the extra tillage.

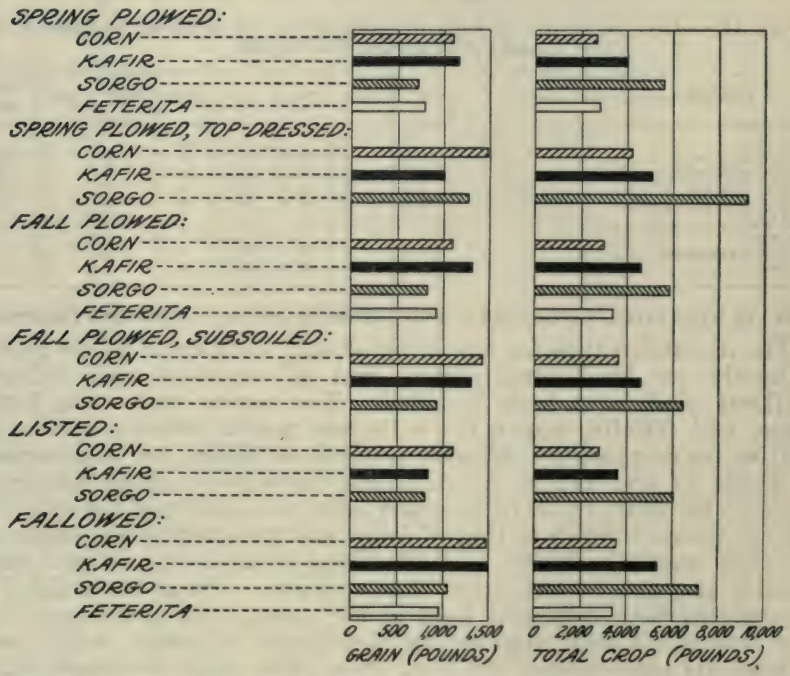


FIGURE 2.—Average yields of corn, kafir, sorgo, and feterita on fallow and continuously cropped by different methods of seed-bed preparation at the Lawton field station for the 14 years 1917–1930

Sorgo on land plowed in the spring yielded 532 pounds of grain and 3,732 pounds of total crop to the acre more when top-dressed with manure than when it was not. Top-dressing was also of distinct advantage as compared with each of the other methods shown. Corn showed a smaller gain from the use of manure, and kafir showed a definite loss in grain yields but an increase in the total crop.

Fallow was not of sufficient advantage with any crop to warrant the practice. Water can not be stored in satisfactory quantities in the soil on which these crops were grown. Insect injury or severe climatic conditions or a combination of both during the growing season may quickly overcome the benefit derived from available moisture stored in the soil.

RESULTS WITH BROOMCORN

During the 14 years from 1917 to 1930, in which tillage experiments have been carried on with broomcorn, three entire failures have been recorded. Drought was the factor responsible for a complete failure in 1918, but the complete failures in 1925 and in 1927 and the partial failures in 1921, 1922, and 1930, were due principally to chinch-bug injury.

Broomcorn is strictly a cash crop, but the stover remaining in the field after the brush is removed is often pastured for a short time. Table 13 shows the results of continuous cropping to broomcorn with different cultural methods from 1917 to 1930, inclusive. Chinch-bug injury has been so prevalent throughout the entire period of this experiment that a quantitative study of the results presented is scarcely justified. The yields of two plots located almost side by side have ranged from 0 to 770 pounds of brush to the acre, with the difference due to the entire destruction of the crop on one plot by chinch bugs. In 1919, 1924, 1926, and 1928, when climatic conditions were favorable to production and chinch-bug infestation and injury were less severe, the fluctuation in yields resulting from different tillage methods was rather small. Broomcorn is grown over a considerable area in the western part of Oklahoma, but the acreage is chiefly confined to sandy soil, where the crop is grown with more certainty than on heavy soils.

TABLE 13.—*Acre yields (in pounds) of broomcorn grown by different methods of tillage at the Lawton field station, 1917-1930*

Previous crop and treatment	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
Broomcorn:															
Spring plowed	370	0	750	440	0	0	223	460	0	420	0	660	150	0	248
Spring plowed, top-dressed	400	0	650	770	770	250	370	510	0	600	0	830	730	280	440
Fall plowed	370	0	850	590	450	0	150	450	0	460	0	570	210	0	293
Fall plowed, subsoiled	330	0	750	580	700	0	260	410	0	410	0	640	300	0	313
Listed, no other preparation [1]	290	0	600	450	0	0	156	340	0	450	0	560	220	0	219
Disked, listed [2]	280	0	500	470	650	210	157	480	0	360	0	560	320	0	285
Average	285	0	550	460	325	105	157	410	0	405	0	560	270	0	252
Fallowed	280	0	650	610	700	0	183	460	0	440	0	590	260	0	298

[1] Beginning with 1921 the land was disked and listed deep.
[2] Beginning with 1921 the land was disked and listed shallow.

RESULTS WITH COTTON

Cotton occupied an important place in the rotation and tillage experiments at the Lawton station during the 14 years from 1917 to 1930. It is well adapted to an elastic system of crop rotations that may necessarily be changed by the individual farmer to meet the fluctuating conditions of climate and other crop hazards. Greater dependence is placed upon it than upon any other crop as a source of income in southwestern Oklahoma. The crop endures the hot, dry summers well, and in the vicinity of Lawton it has only once suffered severely from insect damage.

TABLE 14.—*Acre yields (in pounds) of cotton lint and seed cotton grown by different methods at the Lawton field station, 1917–1930*

LINT

Treatment and previous crop	Plots averaged [1]	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average 1917–1930	Average 1920–1930
Spring plowed:																	
Cotton	1	220	0	360	446	150	110	90	300	190	310	470	170	180	40	217	223
Corn	1	------	------	------	423	140	145	89	410	240	210	540	220	220	60	------	245
Peanuts	1	------	------	------	427	160	130	110	370	280	340	450	250	230	50	------	254
Cowpeas	1	------	------	------	403	130	155	90	360	330	300	440	240	210	70	------	248
Wheat	2	------	------	------	------	------	------	100	260	170	230	475	170	225	50	------	[2] 210
Average	------	220	0	360	425	145	135	96	340	242	278	475	210	213	54	228	238
Spring plowed, top-dressed:																	
Cowpeas	1	------	------	------	458	160	200	90	380	320	290	470	240	240	70	------	265
Disked:																	
Cowpeas	2	------	------	------	------	------	------	90	355	235	215	610	230	240	90	------	[2] 258
Fall plowed:																	
Cotton	7	220	0	380	479	170	108	116	291	211	231	536	173	213	56	227	235
Milo [3]	1	360	0	400	434	160	200	120	450	200	410	610	210	240	60	275	281
Wheat	5	275	0	370	336	155	155	------	219	182	234	476	196	220	60	[4] 221	[5] 223
Cowpeas	3	200	0	450	391	127	150	140	400	340	270	610	290	290	80	267	281
Corn	1	------	------	------	------	------	------	220	450	230	230	630	230	290	90	------	[2] 296
Oats	1	------	------	------	427	180	120	160	320	280	270	450	180	230	90	------	246
Sweetclover	2	------	------	------	------	------	145	80	465	165	160	555	180	275	65	------	[6] 232
Sorgo (drilled)	1	------	------	------	------	------	------	100	530	190	290	630	210	300	50	------	[2] 288
Average	------	264	0	400	413	158	146	134	391	225	262	562	209	257	69	249	257
Fall plowed, top-dressed:																	
Wheat	1	------	------	------	------	------	------	------	250	170	220	500	200	220	40	------	[7] 229
Fall plowed, subsoiled:																	
Cotton	1	240	0	350	451	130	150	130	320	280	290	520	210	220	80	241	253
Fall plowed, spring listed:																	
Cotton	1	200	0	310	522	170	150	120	280	220	320	510	220	190	50	223	250
Listed:																	
Cotton	2	160	0	250	297	80	90	85	215	165	305	360	135	150	40	167	175
Green manured:																	
Cowpeas	2	------	------	------	435	150	200	110	320	310	265	490	250	220	75	------	257
Fallowed	2	250	0	350	314	135	165	135	310	265	345	510	235	255	70	239	249
Fallowed, manured	1	------	------	------	280	170	200	170	390	380	330	550	260	310	100	------	285
Fallowed, top-dressed	1	------	------	------	223	160	140	110	350	270	210	520	230	240	90	------	231

Spring plowed:																	
Cotton	1	600	0	1,020	1,230	410	310	260	780	460	860	1,180	460	470	110	582	594
Corn	1				1,185	390	415	255	1,080	590	550	1,430	590	610	180		661
Peanuts	1				1,205	450	380	310	980	670	860	1,170	670	590	130		674
Cowpeas	1				1,122	385	450	260	950	810	730	1,130	630	550	190		655
Wheat	2							280	690	415	530	1,210	460	575	115		[2] 534
Average		600	0	1,020	1,186	409	389	273	896	589	706	1,224	562	559	145	611	631
Spring plowed, top-dressed:																	
Cowpeas	1				1,305	460	580	250	1,000	820	740	1,210	660	600	180		710
Disked:																	
Cowpeas	2							245	930	605	585	1,550	600	625	225		[2] 671
Fall plowed:																	
Cotton	7	610	0	1,100	1,339	478	308	321	760	539	623	1,359	486	564	147	617	629
Milo [3]	1	990	0	1,150	1,228	460	590	330	1,180	510	1,120	1,620	560	630	180	753	764
Wheat	5	770	0	1,050	1,000	465	425		574	428	594	1,208	532	560	164	[4] 598	[5] 595
Cowpeas	3	550	0	1,310	1,106	370	417	400	1,050	840	720	1,630	770	760	210	724	752
Corn	1							600	1,170	590	640	1,620	610	750	240		[2] 778
Oats	1				1,200	510	340	430	830	670	680	1,180	490	590	210		648
Sweetclover	2						405	220	1,215	440	420	1,415	510	730	185		[6] 616
Sorgo (drilled)	1							300	1,390	490	800	1,640	590	820	130		[2] 770
Average		730	0	1,153	1,175	457	414	372	1,021	563	700	1,459	569	676	183	677	690
Fall plowed, top-dressed:																	
Wheat	1								660	450	550	1,270	540	560	110		[7] 591
Fall plowed, subsoiled:																	
Cotton	1	670	0	980	1,265	360	420	330	850	650	800	1,330	570	580	220	645	670
Fall plowed, spring listed:																	
Cotton	1	560	0	890	1,400	470	400	330	720	500	880	1,280	590	490	140	618	655
Listed:																	
Cotton	2	450	0	715	820	240	255	250	565	390	825	915	365	355	125	448	464
Green manured:																	
Cowpeas	2				1,243	420	580	320	835	805	665	1,305	675	575	195		693
Fallowed	2	690	0	1,020	860	390	465	375	805	680	890	1,305	640	680	190	642	662
Fallowed, manured	1				785	490	570	490	1,020	990	820	1,450	720	810	260		764
Fallowed, top-dressed	1				625	480	410	320	920	690	540	1,360	650	620	240		623

[1] Not all continuous for entire period.
[2] 8-year average.
[3] Milo replaced by feterita beginning 1924.
[4] 13-year average.
[5] 10-year average.
[6] 9-year average.
[7] 7-year average.

In 1924 grasshoppers ravaged the cotton seriously and in many instances disastrously, and vigorous and persistent protective measures were necessary to save the crop. The cotton-leaf worm, the bollworm, and the webworm frequently are present during parts of the growing season and are sometimes responsible for more or less local damage.

The 14 years' results with cotton at the Lawton station are presented in Table 14 and Figure 3.

Only one entire failure was recorded in the 14 years, and that was in 1918, when all the other crops grown at the station failed or were very poor.

Where cotton followed cotton the time of plowing had a negligible influence on the 14-year average of lint. The differences between the annual yields of lint were always small, except in 1926, when spring plowing produced 79 pounds of lint to the acre more than fall plowing, and in 1927, when fall plowing produced 66 pounds of lint to the acre more than spring plowing.

The yields of cotton following corn, drilled sorgo, milo, and feterita were relatively high, but this may be partly due to the favorable location of the rotations containing these crops.

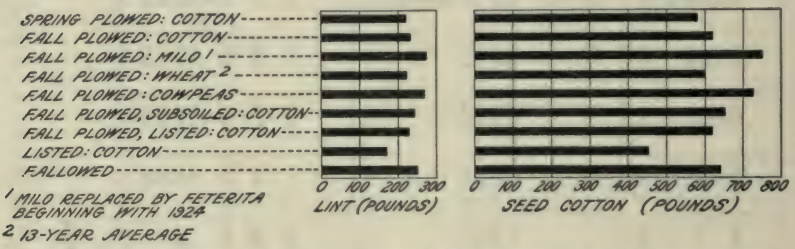


FIGURE 3.—Average acre yields of cotton grown by different methods at the Lawton field station for the 14 years 1917–1930

Cotton appears to do particularly well after cowpeas. On fall plowing it averaged, for the 14 years, 40 pounds more lint to the acre following cowpeas than following cotton. Fall plowing wheatland as a method of preparation for cotton proved to be satisfactory during the 13 years that it was tried. Subsoiling did not show a marked advantage. If the cost of production were taken into account, this method would not be at all feasible.

Lister planting without previous cultivation gave the poorest results of any method tried. The average yield of 167 pounds of lint to the acre was 50 pounds less than the yield from continuous cropping on spring-plowed land and 60 pounds less than that of cotton following cotton on fall plowing. As compared with the average of all fall plowing, listing showed a loss of 82 pounds of lint to the acre. If the average yield of cotton after milo is eliminated from the average of all fall plowing, listing still shows a loss of 71 pounds of lint to the acre. When the land was plowed in the fall and lister planted in the spring there was a gain of 66 pounds of lint to the acre over lister planting without other preparation. The yields by this method were slightly better than those from surface planting on either fall or spring plowing.

Fallow has been of no benefit whatever to cotton, even in years when the production under all other methods was low. In many instances yields from continuous cropping or following other crops equaled or exceeded the yields obtained on fallow.

Beginning with 1920 and 1923, a greater number of crop arrangements and systems of crop sequence than in previous years were available for study, as shown in Table 14.

In several instances these show considerable differences in the yields of cotton due to the time of plowing, the average results being in favor of plowing in the fall. Cotton grown on cowpea land under five methods of tillage from 1923 to 1930, inclusive, produced the following yields of lint in pounds to the acre: Disked, 258; spring plowed, 255; spring plowed and top-dressed, 263; fall plowed, 303; and green manured, 255. When corn was the previous crop during the eight years 1923 to 1930, inclusive, there was a difference of 47 pounds of lint to the acre in favor of fall plowing. On fall-plowed land previously cropped to wheat or oats the greater yield was obtained following oats. On fall-plowed sweetclover land, from 1922 to 1930, inclusive, cotton produced a yield about average as compared with the yield under other methods. The sweetclover, however, frequently failed to make a good stand in the spring or died during the droughty periods in the summer. Weeds and crabgrass usually supplant sweetclover under such conditions, and the succeeding crop of cotton requires considerable extra tillage. A high average yield was produced on spring-plowed peanut land, but little importance should be attached to this method, as the tight upland is not adapted to the production of peanuts. Furthermore, peanuts were destroyed by rabbits in 1925, 1926, 1927, and 1930. In 1928 the seed failed to germinate, and a late planting of cowpeas was substituted, as was also done in 1930. In 1922 the peanut crop was a failure.

A top-dressing of manure applied to spring-plowed cowpea land increased the yield of lint 17 pounds to the acre. Using cowpeas as a green-manure crop for cotton did not prove worth while. The average acre yield of lint for 11 years on manured fallow was 36 pounds higher than on ordinary fallow and 54 pounds higher than on fallow top-dressed with manure.

RESULTS WITH WHEAT

Wheat has been grown under a wide range of methods during the 14 years from 1917 to 1930. A satisfactory combination and arrangement of wheat with other crops has been difficult. This was due to the disastrous results caused by heavy migration of chinch bugs, usually present in the wheat, to adjoining row crops. In order to alleviate this condition as much as possible, it became necessary to revise many of the rotations and to change others to new locations. This action necessarily broke the continuity of many of the experiments, terminated others, and made possible the addition of new experiments. Table 15 shows that wheat yields are subject to wide fluctuations from year to year regardless of the methods employed in production. In 1918 the yields ranged from 0 to 9.2 bushels per acre and in 1922 from 0 to 6.5 bushels, with no single method outstanding in avoiding inconsequential yields. On the other hand, in 1924 the lowest acre yield recorded was 32.8 bushels and the highest 46 bushels.

TABLE 15.—*Acre yields (in bushels) of wheat grown by different methods at the Lawton field station, 1917–1930*

Treatment and previous crop	Plots averaged [1]	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average			
																1917–1930	1917–1922	1920–1930	1924–1930
Late plowed: Wheat	1	5.8	0	24.3	26.3	12.7	1.5	-------	40.3	3.3	23.2	17.3	11.8	9.8	6.7	[2] 14.1	11.8	[3] 15.3	16.1
Early plowed: Wheat	5	11.2	2.7	27.7	22.8	13.8	2.7	-------	37.1	3.8	28.5	16.0	15.5	9.7	6.4	[2] 15.2	13.5	[3] 15.6	16.7
Early plowed, subsoiled: Wheat	1	13.3	3.3	25.7	26.2	12.5	1.7	-------	33.2	3.3	27.5	17.5	16.3	9.5	6.0	[2] 15.1	13.8	[3] 15.4	16.2
Average	-------	10.1	2.0	25.9	25.1	13.0	2.0	-------	36.9	3.5	26.4	16.9	14.5	9.7	6.4	[2] 14.8	13.0	[3] 15.4	16.3
Listed: Wheat	2	14.9	2.2	24.0	21.4	14.8	2.5	-------	43.0	5.5	25.0	17.7	15.5	8.3	4.3	[2] 15.3	13.3	[3] 15.8	17.0
Listed, manured: Wheat	1	20.6	0	17.2	26.7	11.5	0	-------	46.0	4.0	27.7	10.3	8.7	6.2	2.5	[2] 14.0	12.7	[3] 14.4	15.1
Fallowed	3	16.6	5.6	27.7	24.4	15.6	3.3	22.0	42.0	12.0	27.0	15.2	25.5	15.7	9.5	18.7	15.5	19.3	21.0
Fallowed, top-dressed	2	23.0	9.2	25.7	17.4	14.6	4.3	33.7	45.0	15.0	25.8	15.2	26.3	24.2	6.2	20.4	15.7	20.7	22.5
Fallowed, manured	1	-------	-------	-------	18.8	18.3	3.7	30.7	46.0	13.2	28.0	13.5	27.5	22.3	6.3	-------	-------	20.8	22.4
Disked: Corn	7	14.8	2.7	23.7	27.1	14.8	1.5	-------	-------	-------	-------	-------	-------	-------	-------	-------	14.1	-------	-------
Fall plowed: Oats	2	-------	-------	-------	17.0	16.5	4.3	17.3	39.5	2.3	27.6	14.2	19.4	9.3	7.0	-------	-------	15.9	17.0
Disked: Cowpeas	4	-------	-------	31.1	20.5	12.6	6.3	19.4	41.0	8.9	25.4	11.5	19.3	11.8	7.0	-------	-------	16.8	18.0
Disked, top-dressed: Cowpeas	1	-------	-------	-------	14.0	15.3	6.5	20.8	40.5	9.5	23.7	13.2	18.2	15.7	5.8	-------	-------	16.9	18.5
Green manured: Cowpeas	2	-------	-------	-------	17.0	13.2	2.8	24.3	44.3	9.1	28.2	11.9	23.5	13.9	8.2	-------	-------	17.9	19.9
Drilled: Cotton	6	-------	-------	-------	19.0	14.0	-------	17.1	32.8	3.6	22.9	10.4	15.6	9.4	2.3	-------	-------	[3] 14.7	13.9
Drilled, top-dressed: Cotton	1	-------	-------	-------	-------	-------	-------	18.3	33.2	6.5	20.7	9.3	11.7	9.8	3.3	-------	-------	-------	13.5
Plowed: Spring barley	1	-------	-------	-------	-------	-------	-------	-------	38.3	3.5	22.2	14.5	18.3	9.5	7.8	-------	-------	-------	16.3
Early disked: Wheat	1	-------	-------	-------	-------	-------	-------	-------	40.2	2.5	26.3	15.8	15.5	8.3	5.7	-------	-------	-------	16.3
Late disked: Wheat	1	-------	-------	-------	-------	-------	-------	-------	34.2	3.8	19.5	11.5	10.2	5.2	3.8	-------	-------	-------	12.6
Disked as needed: Wheat	1	-------	-------	-------	-------	-------	-------	-------	34.3	5.7	22.8	15.3	14.0	4.8	5.0	-------	-------	-------	14.6

[1] Greatest number at one time. Not continuous for entire period.

[2] 13-year average.

[3] 10-year average.

The average acre yield from all methods was 3.2 bushels in 1918 and 39.5 bushels in 1924. With such wide variations in yields, it is essential that results should cover a long period to be of definite value. The apparent advantage or disadvantage of one method of production as compared with another is of little importance if the results cover only a few years, because even wide differences shown in a short period may be eliminated or reversed in a longer period.

The difference in average yields, for 13 years, of wheat following wheat on late plowing, early plowing, subsoiling, listing, and manured listing was only 1.3 bushels to the acre. Early plowing, listing, and subsoiling were done from July 11 to August 13, usually about the middle of July. Early plowing was done to a depth of 7 to 8 inches. Late plowing was done to a depth of 4 inches from September 19 to October 15, but usually the latter part of September. Manure applied to wheat on listed land produced a rapid and increased growth of straw, but had little effect on the average yield of grain. The average yield of wheat on fallow and top-dressed fallow from 1917 to 1930, inclusive, was only 3.9 and 5.6 bushels to the acre, respectively, more than the average of wheat after wheat on the several methods of fall plowing and subsoiling.

During the years 1917 to 1922, inclusive, early plowing, subsoiling, manuring, and listing had a distinct advantage over late plowing in only one year, 1917. The average acre yield of wheat after wheat on all methods for the six years was 13 bushels, and on disked corn ground for the same period only 14.1 bushels. There was practically no difference in the average acre yields obtained from fallow and top-dressed fallow, and the average of both methods was only 1.5 bushels more than from disked corn ground and 2.6 bushels more than from wheat after wheat.

In the period from 1919 to 1924 the experiments included 10 additional methods of wheat production. Excluding yields from fallow methods, the greatest difference in the average yields during the period 1920–1930 was 3.5 bushels to the acre. The lowest average yield for this period was on listed manured wheatland and the highest was on cowpeas turned under for green manure. The increases obtained on fallow were not enough to make this method practicable. Neither did green manuring prove feasible. When cowpeas are harvested for hay and the land is disked in preparation for wheat, satisfactory yields usually are obtained with a minimum of labor. Although the average yield of wheat drilled on cotton is slightly less than that on disked cowpea land, the method is practicable and adapted to systems of crop diversification.

Methods designed to insure maximum safety in production or those in which cost of production is high did not give satisfactory results. The variations between methods of production in a single year or in a period of years are unimportant as compared with the wide fluctuations to which all methods of production are subject. The results presented indicate that wheat production should be adjusted to suit the individual farm and its equipment. Although a satisfactory average yield over a long period of years may be expected, the large annual fluctuations demand that the production be planned on a thoroughly economical basis that will carry the grower through the years of low yields.

RESULTS WITH OATS

In southwestern Oklahoma oats have always been considered important as a dependable source of early feed for work stock.

In Table 16 the annual and average yields of oats on fall-plowed cotton land and on alfalfa sod may be compared directly for the 14 years from 1917 to 1930. Oats on alfalfa sod are grown in a 6-year rotation that contains three years of alfalfa, one plot being broken in the late summer for the succeeding crop of oats. Oats on fall-plowed cotton are grown in a 4-year rotation of cowpeas, cotton, oats, and kafir. All crops in this rotation are grown on fall or winter plowing with manure disked into oat land in the winter for kafir.

TABLE 16.—*Acre yields (in bushels) of oats, winter barley, and spring barley grown by different methods at the Lawton field station, 1917–1930*

Crop	Treatment and previous crop	1917	1918	1919	1920	1921	1922	1923	1924
Oats	Fall plowed: Alfalfa	6.6	0	15.6	62.8	37.2	54.7	44.7	34.1
Do	Fall plowed: Cotton	5.0	0	12.2	79.7	47.5	42.2	49.1	85.6
Do	Fall plowed: Wheat	------	------	------	53.1	33.4	32.8	55.0	52.5
Do	Disked: Cotton	------	------	------	55.7	28.8	41.1	41.9	68.8
Do	Disked: Wheat	------	------	------	------	------	------	37.2	53.8
Winter barley	Disked: Cowpeas	------	------	------	------	------	------	11.7	69.2
Spring barley	do	------	------	------	------	------	------	8.5	31.3
Do	Disked: Wheat	------	------	------	------	------	------	13.8	22.9

Crop	Treatment and previous crop	1925	1926	1927	1928	1929	1930	Average		
								1917–1930	1920–1930	1923–1930
Oats	Fall plowed: Alfalfa	17.8	45.9	25.0	45.0	30.9	22.5	31.6	38.2	33.2
Do	Fall plowed: Cotton	19.1	52.2	22.5	36.6	25.0	25.9	35.9	44.1	39.5
Do	Fall plowed: Wheat	22.2	29.1	18.8	32.8	25.3	39.1	------	35.8	34.4
Do	Disked: Cotton	23.1	52.5	18.1	34.7	27.8	44.4	------	39.7	38.9
Do	Disked: Wheat	21.9	33.4	21.3	22.2	24.1	25.9	------	------	30.0
Winter barley	Disked: Cowpeas	0	48.3	29.4	16.7	11.0	4.2	------	------	23.8
Spring barley	do	1.9	21.3	2.5	13.8	12.3	8.3	------	------	12.5
Do	Disked: Wheat	5.4	20.6	3.5	13.1	14.4	7.7	------	------	12.7

Oats grown on fall-plowed cotton land outyielded those grown on alfalfa sod during the 14 years that the two methods were under trial. The 14-year average yield from 1917 to 1930, inclusive, showed a gain of 4.3 bushels to the acre in favor of fall-plowed cotton land. In the 11-year period 1920–1930 and the 8-year period 1923–1930 the gains were 5.9 and 6.3 bushels to the acre, respectively. In a comparison of four methods of production that became available from 1920 to 1930, inclusive, oats on fall-plowed cotton land outyielded all other methods. The average yield on disked cotton land, however, was only 4.4 bushels to the acre less. Oats on fall-plowed wheatland yielded 8.3 bushels to the acre less than on fall-plowed cotton land, and growing the crop in this manner proved to be the poorest of the methods compared. During the eight years from 1923 to 1930, inclusive, one additional method—oats on disked wheatland—was added. Growing oats on cotton land either disked or fall plowed proved to be the best method of production. During this period there was a difference of 9.5 bushels to the acre between the lowest and the highest average yields.

RESULTS WITH BARLEY

Spring barley has been grown only to a very limited extent, because of its apparent inability to give satisfactory results. Winter barley, on the other hand, has gained so rapidly in acreage since 1919 that it is now recognized as an important crop in western Oklahoma. Both winter and spring barley are subject to the menace of crop insects, and their location with respect to grain sorghums, forage sorghums, and corn must necessarily be arranged with considerable care.

Results for eight years are available for winter and spring barley and are presented in Table 16. Spring barley produced a little more than half as much as winter barley during the eight years. The annual yields of winter barley ranged from 0 to 69.2 bushels to the acre, and the annual yields of spring barley ranged from 1.9 to 31.3 bushels to the acre. Spring barley on disked cowpea land and on disked wheatland gave practically the same results for the eight years, and the average of both methods was 11.2 bushels to the acre less than that of winter barley on disked cowpea land.

Winter barley was entirely winterkilled in 1925 and 1930. In 1930 winter barley was reseeded February 14, and a yield of 4.2 bushels to the acre was produced under very unfavorable spring climatic conditions. Both crops usually suffer from severe chinch-bug injury and require climatic conditions that are favorable to early maturity.

COMPARATIVE YIELDS OF WHEAT, OATS, AND BARLEY

In Table 17 are given the number of pounds of grain produced per acre by wheat and oats under two comparable methods for the 11 years 1920–1930, also the quantity of grain produced by wheat, winter barley, and spring barley on disked cowpea land for the 8 years 1923–1930. In 10 comparable years oats produced 148 pounds to the acre more than wheat on fall-plowed wheatland, and in the same number of years the difference on cotton land was 429 pounds to the acre in favor of oats. The cotton land was disked for a spring seeding of oats, and the wheat was sown between the cotton rows with a 1-horse drill. In order to facilitate a uniform seeding, a 1-horse harrow preceded the wheat drill.

TABLE 17.—*Acre yields (in pounds) of wheat and oats following wheat and cotton and of wheat, winter barley, and spring barley following cowpeas at the Lawton field station, 1920–1930*

Crop	Treatment and previous crop	1920	1921	1922	1923	1924	1925
Wheat	Early fall plowed: Wheat	1,370	825	160	-------	2,228	226
Oats	Fall plowed: Wheat	1,700	1,070	1,050	1,760	1,680	710
Wheat	None: Cotton	1,140	840	-------	1,028	1,967	218
Oats	Disked: Cotton	2,000	1,160	1,430	1,340	2,200	740
Wheat	Disked: Cowpeas	-------	-------	-------	1,150	2,485	540
Winter barley	do	-------	-------	-------	560	3,320	0
Spring barley	do	-------	-------	-------	410	1,500	90

Crop	Treatment and previous crop	1926	1927	1928	1929	1930	Average	
							1920–1930	1923–1930
Wheat	Early fall plowed: Wheat	1,710	958	930	582	382	[1] 937	[2] 1,002
Oats	Fall plowed: Wheat	930	600	1,050	810	1,250	1,146	1,099
Wheat	None: Cotton	1,377	622	937	565	135	[1] 883	856
Oats	Disked: Cotton	1,680	580	1,110	890	1,420	1,323	1,245
Wheat	Disked: Cowpeas	1,615	770	1,190	770	415	-------	1,117
Winter barley	do	2,320	1,410	800	530	200	-------	1,143
Spring barley	do	1,020	120	660	590	400	-------	599

[1] 10-year average. [2] 7-year average.

During the eight years that wheat, winter barley, and spring barley were grown on disked cowpea land there was but little difference between the yields of wheat and winter barley, but both exceeded the average yield of spring barley by 518 and 544 pounds to the acre, respectively.

RESULTS WITH COWPEAS

Cowpeas have been used quite extensively in the rotations and tillage methods, in order to test their value as a legume crop in soil improvement and because of the comparative ease of preparing a seed bed for the crop subsequent to cowpeas. The cowpeas have been grown in cultivated rows, being planted about May 15, and harvested as a hay crop when the first pods began to turn brown. The quantity of seed produced varies somewhat with climatic conditions, but depends more directly upon the variety. From 1916 to 1920, inclusive, the Early Brabham variety was grown on the rotation plots. This is a coarse-growing, late-maturing variety that produces a very small amount of seed. From 1921 to 1928, inclusive, the Early Buff was used. This variety is a semierect type, matures early, and produces a medium growth of vine and usually an abundant quantity of seed. In 1929 and 1930 a Chinese importation, white seeded with a pinkish-brown eye, was used. This selection resembles the Black Eye cowpea in growth, but appears to be more prolific in the production of seed and fully as good in the production of hay.

The yields of cowpeas obtained during the 14 years from 1917 to 1930, inclusive, are shown in Table 18. The average yield for the 12 years 1919–1930 on fall-plowed kafir land exceeded that on spring-plowed kafir land by 335 pounds to the acre. Fall plowing again showed an increase of 398 pounds to the acre for the 11 years 1920–1930. When cowpeas were grown on milo land the difference between spring plowing and fall plowing for the 11 years amounted to 164 pounds in favor of the latter. Spring-plowed wheat and kafir land showed a difference of only 41 pounds to the acre in favor of kafir land. There was but little difference between the average yields of cowpeas on spring-plowed and fall-plowed cotton land, but the average of both methods was only 44 pounds to the acre less than the average of both spring and fall plowing on kafir land. Taken as a whole, the average yield of cowpeas on spring-plowed land for 11 years is only 180 pounds to the acre less than the average on fall-plowed land. These differences are not so important when it is considered that the yields represent the total crop in the form of field-cured hay. However, cowpeas have demonstrated considerable dependability of production and have averaged nearly 1 ton of field-cured hay to the acre.

TABLE 18.—*Acre yields (in pounds) of cowpeas grown by different methods at the Lawton field station, 1917–1930*

Treatment and previous crop	Plots averaged [1]	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average		
																For varying periods	1919–1930	1920–1930
Spring plowed:																		
Wheat	2	------	700	5,200	2,000	2,250	2,100	1,150	2,200	1,275	975	2,300	1,425	3,475	1,200	[2] 2,019	2,129	1,850
Kafir	5	------	------	4,700	3,160	2,010	2,300	1,400	1,850	1,000	1,167	2,467	1,467	2,917	1,067	------	2,125	1,891
Milo [3]	2	------	------	4,525	2,575	1,975	2,550	1,450	1,725	1,050	1,075	2,550	1,000	2,775	975	------	2,019	1,791
Cotton	3	------	------	------	3,000	2,717	2,067	1,250	2,200	1,400	1,100	2,150	1,500	3,533	1,217	------	------	2,012
Average	------	------	700	4,808	2,684	2,238	2,254	1,313	1,994	1,181	1,079	2,367	1,348	3,175	1,115	[2] 2,020	2,130	1,886
Fall plowed:																		
Kafir	2	6,000	1,200	4,350	3,300	3,225	2,500	1,850	2,200	1,275	1,125	3,075	1,625	3,800	1,200	[4] 2,623	2,460	2,289
Milo [5]	1	------	------	2,700	1,750	2,800	2,400	1,650	2,200	1,200	1,050	2,800	1,400	2,800	1,450	------	2,017	1,955
Cotton	4	------	------	------	3,600	2,500	2,000	1,400	2,230	1,213	1,225	2,538	1,513	3,413	1,238	------	------	2,079
Wheat	3	------	------	3,100	2,900	2,367	2,150	------	------	------	------	------	------	------	------	[6] 2,629	------	------
Sorgo	1	------	------	------	2,750	2,550	2,350	------	------	------	------	------	------	------	------	[7] 2,550	------	------
Sudan	1	------	------	------	3,150	2,200	2,100	950	------	------	------	------	------	------	------	[6] 2,100	------	------
Sweetclover	1	------	------	------	3,100	2,200	------	------	------	------	------	------	------	------	------	[8] 2,650	------	------
Average	------	6,000	1,200	3,383	2,936	2,549	2,250	1,463	2,210	1,229	1,133	2,804	1,513	3,338	1,296	[4] 2,379	2,175	2,066
Fall list: Kafir	1	------	------	------	1,800	1,350	1,350	------	------	------	------	------	------	------	------	[7] 1,500	------	------

[1] Greatest number at any one time. Not all continuous for entire period.
[2] 13-year average.
[3] Milo replaced by feterita beginning 1925.
[4] 14-year average.
[5] Milo replaced by feterita beginning 1924.
[6] 4-year average.
[7] 3-year average.
[8] 2-year average.

RESULTS WITH ALFALFA

Alfalfa has been successfully grown on the station in fields not suitable for plot work, but in rotation experiments it has been confined to one 6-year rotation. This provides for seeding each year a plot that is to grow continuously for three years. From 1917 to 1921, inclusive, the alfalfa was grown on fall-plowed wheat stubble. From 1922 to 1930, inclusive, the alfalfa was seeded on disked cotton land. Seeding was always done as soon as practicable in the spring, when soil-moisture conditions were favorable for germination and the danger from killing frost was past. Fall seeding, however, is practiced almost exclusively by farmers. When there is sufficient moisture in the fall to insure germination, this method of seeding results in an early growth in the spring, essential in preventing the growth of noxious weeds and grasses.

From 1919 to 1930, inclusive, one of the three plots in this 6-year rotation was grown in 44-inch rows and cultivated to prevent weed growth. Under this arrangement it is not possible to compare the yields of hay obtained from row plots and broadcast plots of the same age. However, the annual and average yields of hay produced by the two methods of seeding may be compared for the 12 years 1919–1930. The hay crop was an entire failure on the rowed plot in 1921 and on the broadcast plots in 1925. The yields of hay on the rowed plot ranged from 0 to 4,750 pounds of hay to the acre. On the broadcast plots the yields ranged from 0 to 6,250 pounds to the acre. The 12-year average yields of hay were 1,619 pounds on the rowed plot and 1,959 pounds on the two broadcast plots.

The first-year acre yields of hay ranged from 750 to 1,750 pounds on the rowed plot four times out of five that it was seeded. The first year's growth averaged 890 pounds of hay to the acre on the rowed plot and 235 pounds to the acre on broadcast plots. In the latter case only two cuttings were secured in the same year that seeding was done. The second-year yields of hay on the rowed plot ranged from 1,450 to 4,750 pounds to the acre, with an average acre yield of 2,530 pounds. The second year's growth of hay on the broadcast plots ranged from 1,500 to 6,250 pounds to the acre, with an average of 2,244 pounds, which was 286 pounds less than that on the rowed plot. The third-year hay yields ranged from 1,000 to 1,650 pounds to the acre for rowed alfalfa and 800 to 5,850 pounds to the acre on broadcast plots. The average yields were 1,317 pounds to the acre on the rowed plot and 2,569 pounds on the broadcast plots. The average yield of hay from all plots, rowed and broadcast, from 1919 to 1930, inclusive, was 1,833 pounds to the acre. For the 14 years 1917–1930 the average was 1,604 pounds.

Alfalfa does not satisfactorily fit into a short rotation, and a correct measure of its production can not be obtained in such an arrangement. The uncertainty and expense of obtaining a good stand makes it inadvisable to plow under an established stand so long as its growth is satisfactory. Grasshoppers were a serious menace to alfalfa in 1924. The plants are susceptible to injury from several other insect pests that are responsible for reduced yields at some time during the season nearly every year. Noxious weeds and grasses generally shorten the life of the stand and frequently constitute a very appreciable percentage of the first cutting of hay in the spring.

RESULTS WITH SWEETCLOVER

White sweetclover (*Melilotus alba*) was grown in two 4-year rotations, from 1917 to 1930, inclusive. The difficulty met in growing this crop and the changes in crops in these rotations make it desirable to consider separately the results obtained in each rotation. The two rotations are designated as No. 133 and No. 134.

In 1916, 1917, and 1918 rotation No. 133 was arranged so that sweetclover was seeded with winter wheat on disked sorgo land and plowed under as a green-manure crop for oats. This practice proved to be so unsatisfactory for the sweetclover as well as for the subsequent crops that it was discontinued. Beginning with 1919, the rotation was changed to provide for seeding sweetclover on disked cowpea land. Under this arrangement sweetclover has been harvested as a hay crop. The yields of hay during the 12 years 1919–1930 ranged from 0 to 3,850 pounds to the acre, the average being 1,340 pounds. The hay frequently contained a very appreciable quantity of grass and weeds. Yields from the second-year growth were obtained in three years only. Weeds, grass, and dry weather so reduced the stand that reseeding was necessary in all but three years.

Rotation No. 134 provided for seeding sweetclover with oats on disked sorgo stubble in 1916, 1917, and 1918. This proved no more satisfactory than the arrangement in rotation No. 133 and was changed at the close of 1918. From 1919 to 1921 sweetclover was seeded on disked wheat stubble. Beginning in 1922, the rotation was revised, and sweetclover was seeded on disked kafir land. The yields obtained during the 14-year period 1917–1930 in rotation No. 134 ranged from 0 to 4,300 pounds to the acre. The average yield for the 14 years was 1,245 pounds to the acre. The hay contained a high percentage of weeds and grass. Dry weather and weeds and grass choked out and killed the stand of sweetclover, making it necessary to reseed every year but three. The average yield of sweetclover for the nine years 1922–1930 was 1,089 pounds to the acre on disked cowpea land in rotation No. 133 and 803 pounds to the acre on disked kafir land in rotation No. 134.

RESULTS WITH PEANUTS

Peanuts were grown on spring-plowed cotton land in a 2-year rotation from 1920 to 1930, inclusive. Rabbits destroyed the growing crop four times, and germination failed once during the 11 years. The average yield of peanuts was 14 bushels to the acre, and the annual yields ranged from 0 to 59.3 bushels to the acre. With very few exceptions the peanuts were of poor quality and very poorly filled out. There was less variation in the annual yields of hay, and it usually was fair in quality. The average yield of peanut hay was 1,294 pounds to the acre. This crop is best adapted to the sandy soils in this section and is grown to a limited extent much more satisfactorily on them than on the heavy upland soils.

SUMMARY AND CONCLUSIONS

The soils in southwestern Oklahoma differ widely in structure and composition, and erosion is a significant problem on most farms.

Rainfall is usually torrential in character, and its distribution is erratic. The summers are long and hot and protracted periods of

drought are frequent. Winter temperatures are generally mild, and the 214-day frost-free period provides a long growing season for a wide range of crops.

Insects are responsible for many low yields and failures.

The investigations do not show any cropping methods that may be depended upon to insure a good crop every year, but well-adapted crops show satisfactory averages over a period of years.

Corn can not be grown successfully on the tight upland.

Kafir is the best adapted of the grain sorghums.

Milo can not be grown successfully, largely because of its susceptibility to chinch-bug damage. Feterita is more susceptible than kafir to such damage, but has a place as a catch crop for feed. The heaviest tonnage of feed is produced by sorgo. Cotton is well adapted to conditions in the section and is its leading cash crop. Winter wheat, winter barley, and spring oats are successfully grown. Cowpeas are the most dependable legumes on upland soils. Alfalfa is more successful and productive than sweetclover.

Wheat did not show a marked response to differences in the time or depth of plowing. Spring-planted crops generally yielded better on fall or winter plowing than they did on spring plowing.

Listing and plowing were of about equal value as preparations for wheat, but listing was inferior to plowing for row crops, because of poor stands and retarded growth in the early season.

Neither small-grain nor row crops responded to fallow, the yields often being as good or better on land cropped each year.

Subsoiling was ineffective in overcoming drought, and did not result in satisfactorily increased yields of any of the important crops.

There is little in the results to recommend the use of green manure. Barnyard manure must be applied with discretion. Either barnyard or green manure may overstimulate early growth that may later fire and result in a reduced yield of grain. Cotton, corn, and sorgo showed small average increases in yield from the application of manure, but the grain yields of kafir and wheat were reduced by such application.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Dry Land Agriculture	C. E. LEIGHTY, *Principal Agronomist, in Charge.*

35

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

TECHNICAL BULLETIN No. 329 NOVEMBER, 1932

EXPERIMENTS IN WHEAT PRODUCTION ON THE DRY LANDS OF OREGON WASHINGTON, AND UTAH

By

DAVID E. STEPHENS

Superintendent, Sherman County Branch Station, Moro, Oreg., and
Senior Agronomist, Division of Cereal Crops and Diseases

H. M. WANSER

Superintendent, Adams Branch Station, Lind, Wash.

and

AARON F. BRACKEN

Superintendent, Nephi Substation, Nephi, Utah, and formerly
Scientific Assistant, Division of Cereal Crops and Diseases, Bureau of Plant Industry

UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - Price 10 cents

TECHNICAL BULLETIN No. 329 November, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

EXPERIMENTS IN WHEAT PRODUCTION ON THE DRY LANDS OF OREGON WASHINGTON, AND UTAH

By DAVID E. STEPHENS, *Superintendent, Sherman County Branch Station, Moro, Oreg.*, and *Senior Agronomist, Division of Cereal Crops and Diseases;* H. M. WANSER, *Superintendent, Adams Branch Station, Lind, Wash.;* and AARON F. BRACKEN, *Superintendent, Nephi Substation, Nephi, Utah,* and formerly *Scientific Assistant, Division of Cereal Crops and Diseases, Bureau of Plant Industry*

In Cooperation with the Agricultural Experiment Stations of Oregon, Washington, and Utah

CONTENTS

	Page
Importance of wheat in the far West	1
Soils	8
Climatic data	9
Precipitation	9
Evaporation	10
Temperature	10
Tillage experiments	11
Treatment of land before plowing	11
Plowing	16
Substitutes for plowing	32
Cultivation of summer fallow	33
Tillage factors influencing yields and quality of winter wheat	42
Harrowing the growing crop	44
Rate and date of seeding experiments	47
Results at Moro	47
Results at Lind	52
Results at Nephi	55
Depth of seeding experiments	58
Results at Moro	58
Results at Lind	59
Spacing and furrow seeding experiments	60
Results at Moro	60
Results at Lind	62
Results at Nephi	65
Summary	66

IMPORTANCE OF WHEAT IN THE FAR WEST

In the agricultural development of the dry lands of the far West, wheat has been the pioneer crop. There are several reasons for this. In sections of high altitude or cool climate, where the winters are not too severe, winter wheat usually will produce more pounds of grain per acre than any other crop, barley being its closest competitor in this respect. Wheat is a crop of wide adaptation, and its price is subject to less fluctuation from year to year than that of other cereals. It always is readily salable, and its value is high in proportion to its bulk. These facts have made wheat a crop of great value to the new settler, who often must haul his crops long distances to market.

Wheat is the most important farm crop grown in the far western United States north of the thirty-seventh parallel of latitude, or the southern boundary of Kansas, Colorado, and Utah. In sections west of the Rocky Mountains where the precipitation is less than 15 inches it is the only crop grown commercially to any considerable extent except where irrigation is practiced. Even on some of the irrigated lands

wheat is extensively grown. In general, however, on the irrigated lands wheat has been largely replaced by such crops as alfalfa, clover, and sugar beets.

Despite its local importance, the total wheat production in the far western United States is not great when compared with that in the Middle Western and North Central States. Table 1 shows the average annual production by 10-year periods since 1881 in Idaho, Washington, Oregon, California, and Utah. No statistics are available for Idaho, Washington, and Utah prior to 1882. The production of wheat in Nevada is unimportant.

TABLE 1.—*Average annual production of wheat in Idaho, Washington, Oregon, California, and Utah by 10-year periods, 1881–1930*

Period	Wheat production (bushels)				
	Idaho	Washington	Oregon	California	Utah
1881 to 1890	[1] 1,093,000	[1] 6,332,000	13,555,000	34,263,000	[1] 1,783,000
1891 to 1900	2,366,000	14,615,000	14,728,000	33,308,000	2,896,000
1901 to 1910	8,323,000	30,661,000	14,548,000	18,739,000	4,477,000
1911 to 1920	17,366,000	43,054,000	18,058,000	8,043,000	6,147,000
1921 to 1930 [2]	26,298,000	45,115,000	21,997,000	12,423,000	5,940,000

[1] 9-year average, 1882 to 1890; no data available for 1881. [2] Preliminary yields used for 1930.

Between 1869 and 1879 from 2,000,000 to 8,000,000 bushels of wheat were produced annually in Oregon. In California the annual production for the same period ranged from 14,000,000 to 40,000,000 bushels. There has been a marked decrease in production in California for the period shown in Table 1, the decrease in the period from 1900 to 1920, inclusive, being attributable primarily to the substitution of barley in certain sections of the State. Since 1920, however, wheat has partly regained its former status.

In Oregon, on the other hand, there has been a gradual increase for the 50-year period, with the exception of the decade 1901 to 1910, when there was a slight reduction. Most of the wheat produced in Oregon is grown in the eastern half of the State.

In Utah the production also has consistently increased during the last five decades with the exception of the period 1921 to 1930, which showed a slight decrease.

There has been an even greater increase in production in Idaho and Washington during the last 50 years. Nearly all of the wheat produced in Washington is grown in the eastern half of the State.

Farm practice usually is the outgrowth of necessity. In the States of Washington, Oregon, Idaho, and Utah climatic conditions are such that successful wheat production on dry lands is based on alternate years of crop and clean fallow. In the development of the summer-fallow system in these States many different methods of cultivating the land have been advocated, and many different tillage methods are still practiced by farmers.

In 1904, experiments to determine the effect of different tillage methods on the yield of wheat were begun at Nephi, Utah, in the Great Basin area. These experiments were conducted cooperatively by the Utah Agricultural Experiment Station and the United States Department of Agriculture from 1908 to 1920. Since 1920 the Utah station has continued the work independently of Federal aid. Simi-

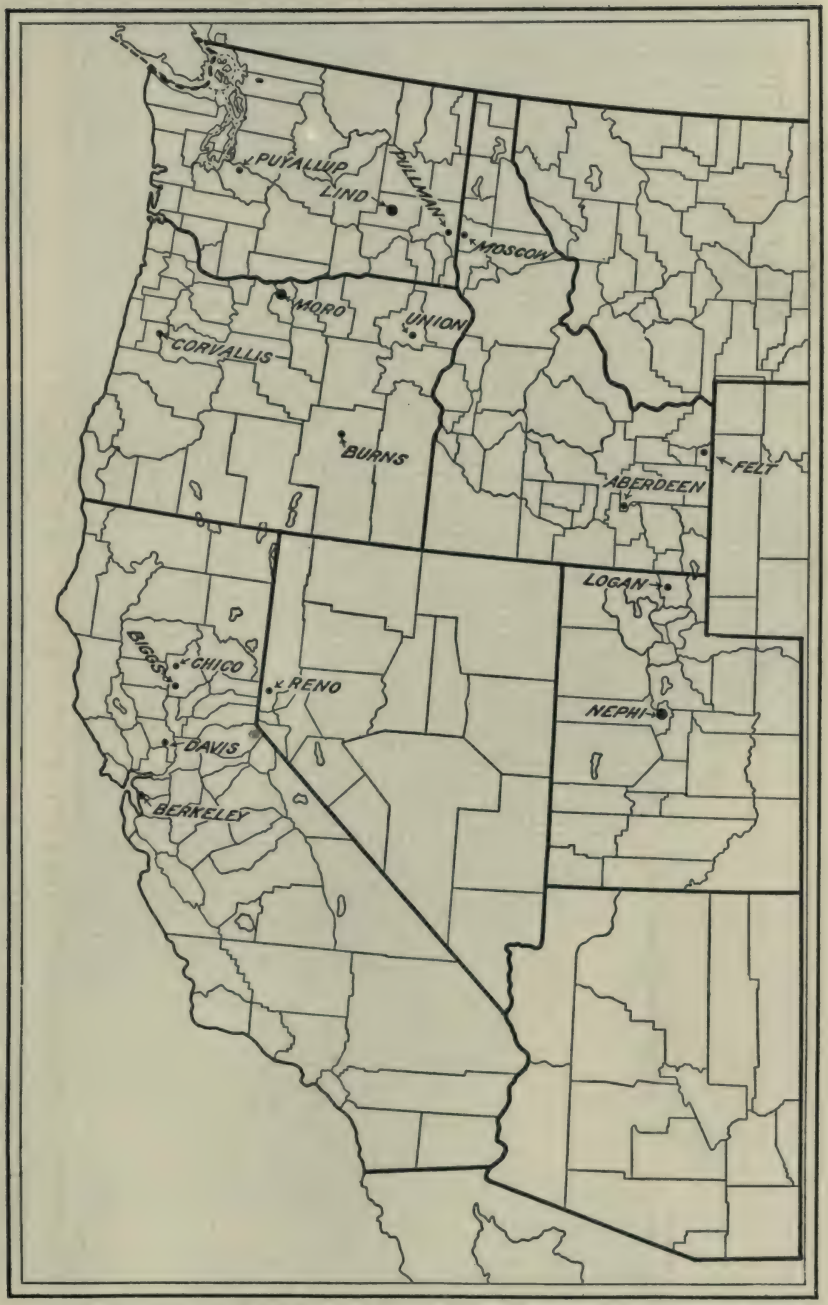


FIGURE 1.—Outline map of seven Western States showing the location of the Sherman County Branch Station, Moro, Oreg., the Adams Branch Station, Lind, Wash., and the Nephi Substation, Nephi, Utah, as well as some of the State agricultural experiment stations and substations and Federal stations

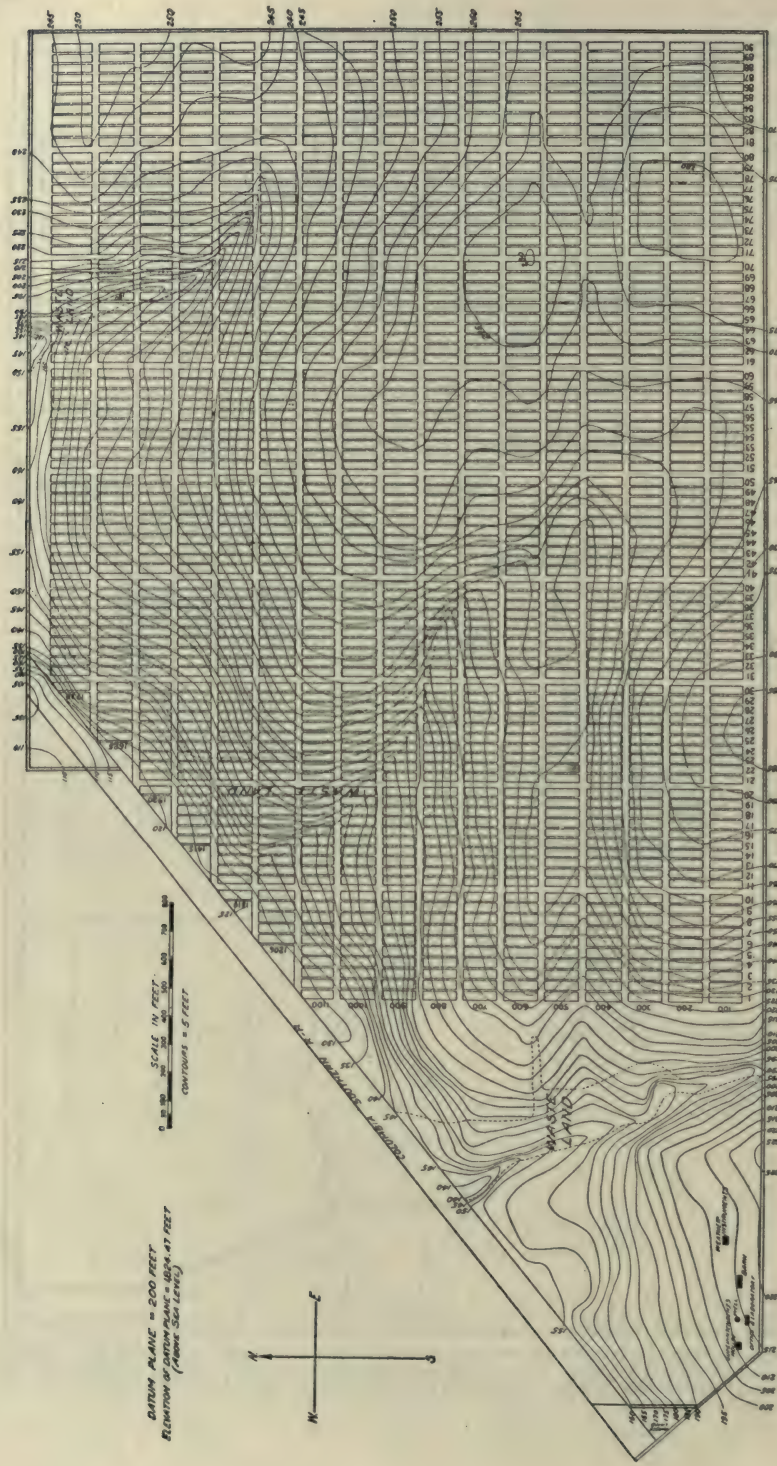


FIGURE 2.—Contour map of the Sherman County Branch Station, Moro, Oreg., showing the method of dividing the farm into plots

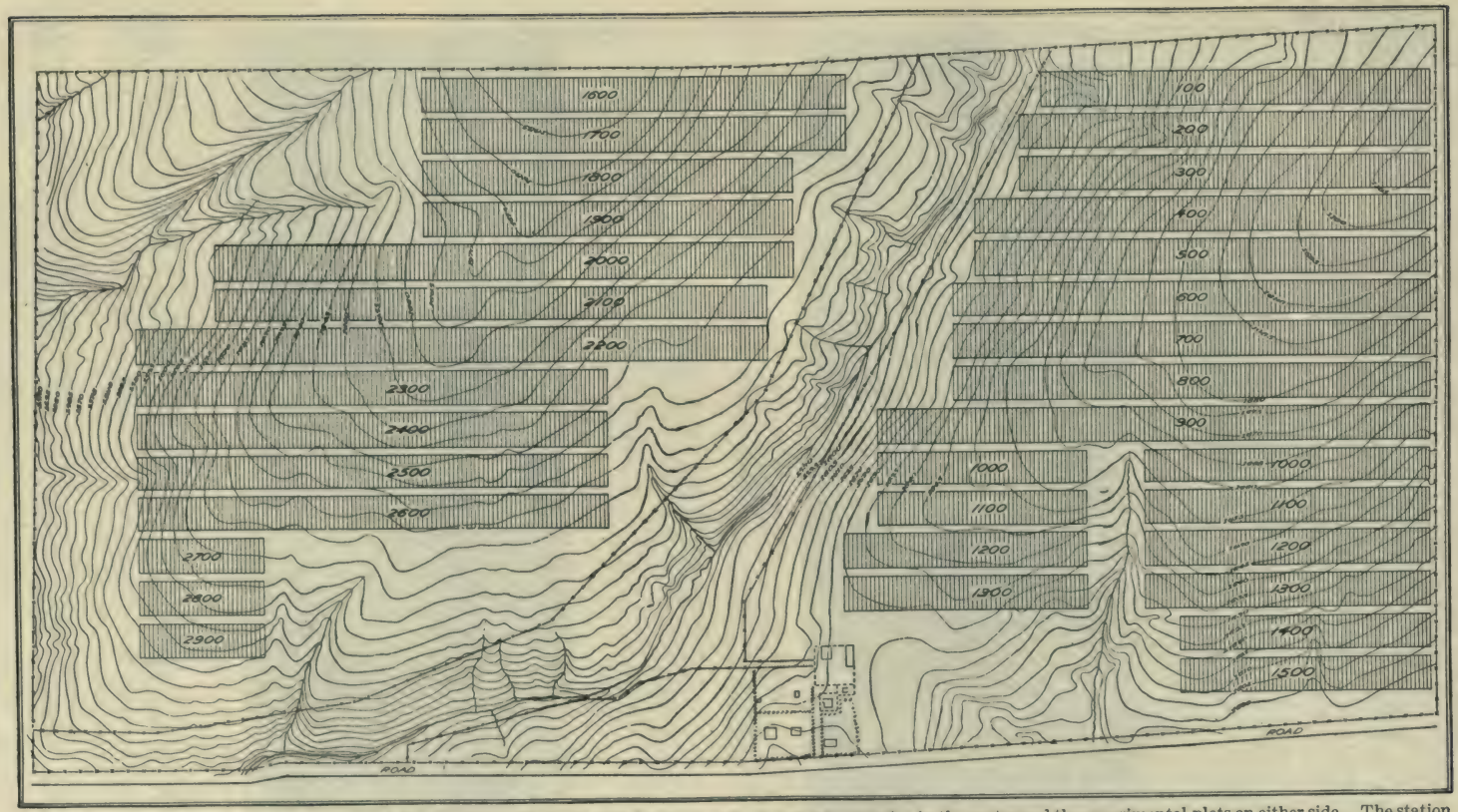


FIGURE 3.—Contour map of the Adams Branch Station, Lind, Wash., in 1918, looking north, showing deep ravine in the center and the experimental plots on either side. The station occupies the southern half of section 32–18–34

lar experiments were begun at Moro, Oreg., in the Columbia Basin, in 1911 and at Lind, Wash., also in the Columbia Basin, in 1916, by the agricultural experiment stations of these States in cooperation with the United States Department of Agriculture. The location of these stations is shown in Figure 1. A wide range of crop experiments is conducted at these stations, but in this bulletin only the

FIGURE 4.—General view of a portion of the Sherman County Branch Station, Moro, Oreg., in June, 1925. The rolling topography of the surrounding country is shown, with some of the station buildings at the left and the town of Moro in the background. The crop in the foreground is field peas in cultivated rows

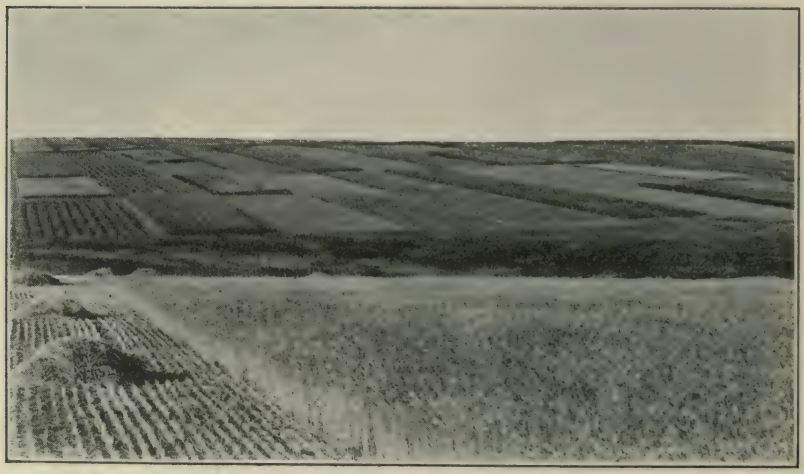


FIGURE 5.—Some of the experimental plots at the Sherman County Branch Station, Moro, Oreg.

results of the tillage experiments and those on the rate, date, and depth of sowing wheat grown after fallow will be presented. Diagrams showing the plotting of the stations at Moro, Oreg., and Lind, Wash., are presented in Figures 2 and 3.

Figure 4 presents a general view of a portion of the Sherman County Branch Station, Moro, Oreg., and the surrounding country, while

Figure 5 shows some of the experimental plots. Figure 6 presents a general view of the Adams Branch Station, Lind, Wash., with the station buildings in the background. The rolling topography of this

FIGURE 6.—Some of the winter-wheat plots at the Adams Branch Station, Lind, Wash., in 1928, with station buildings in the background. The rolling topography and the method of seeding roadways and alleys are shown

section is shown in this illustration, also the method of seeding roadways to prevent soil blowing.

FIGURE 7.—Station buildings at the Nephi Substation, Nephi, Utah

Figure 7 shows the buildings at the Nephi Substation, Nephi, Utah, and Figure 8 a field of uncultivated fallow land on this station farm.

FIGURE 8.—Uncultivated fallow at the Nephi Substation, Nephi, Utah. The station lies on a transverse ridge in a narrow valley between two ranges of mountains

SOILS

The altitude of the station at Moro, Oreg., is approximately 1,800 feet. The soil is a silt loam, classified by the United States Bureau of Chemistry and Soils as Yakima silt loam. It is rather light in texture, but the percentage of sand is not so high that there is any trouble from the soil drifting with the wind, as do some other soils in this section. It is representative of large areas in the Columbia Basin of Oregon.

The average moisture content of the soil to a depth of 6 feet at the Moro station after a season of fallow rarely exceeds 14 per cent. A winter-wheat crop usually reduces this moisture content to about 5 per cent in the upper 6 feet. The soil is underlain with basalt, the depth from the surface to this basalt varying from 2 to 7 feet. The productivity of the soil is considerably influenced by its depth, the shallow soils being less productive than the deep ones, because of their inability to store sufficient moisture.

The soils at the Lind station are basaltic in origin and have been more or less modified by wind. The soil, a very fine sandy loam of the Ritzville series, is considerably lighter than that at Moro and is more subject to drifting or blowing by the wind. The soil depth varies from 10 to 50 feet, and the texture is remarkably uniform throughout the entire depth. The topography, like that at Moro, is rolling, the entire dry-farming area of the Columbia River Basin being a plateau cut by dry canyons or coulees. The altitude of the station at Lind is 1,600 feet.

During most of the years in which the experiments herein reported were conducted the moisture at Lind usually has been sufficient to penetrate the soil to a depth of only about 4 feet except in 1927 and 1928. The average moisture content of the soil seldom exceeded 10 per cent, even after a season of fallow. The moisture content after growing a crop of winter wheat is about 3.8 per cent in the upper 4 feet of soil.

The altitude of the Nephi Substation is 5,300 feet. The soil is a rather heavy clay loam derived from the weathering of adjacent

mountain ranges. Below the third foot the percentage of silt and sand increases, and at about the seventh foot there is a stratum of heavy blue clay of rather high moisture content. The average moisture content of the first 6 feet usually is about 20 per cent in the spring after being fallowed the previous summer. A winter-wheat crop usually reduces the moisture content of this layer of soil to about 9 per cent.

CLIMATIC DATA

PRECIPITATION

Of the climatic factors influencing crop production, the precipitation and its distribution throughout the year are the most important in the dry-farmed areas of the far West. High yields of wheat usually are associated with years of heavy rainfall during the growing season, or the months of April, May, and June. Table 2 shows the precipitation by months and the total annual precipitation at Moro, Lind, and Nephi. The records at Moro are for the years 1910 to 1929, inclusive; at Lind for the years 1916 to 1930, inclusive; and at Nephi for the years 1898 to 1929, inclusive. In this connection it should be borne in mind that the precipitation at Lind during much of this period was below normal. It varied from 4.25 inches in 1929 to 13.16 inches in 1927. In the nine crop years 1897 to 1906 the average precipitation at Lind was 11.8 inches, as compared with 7.82 inches in the period of these experiments.

TABLE 2.—*Average monthly and annual precipitation at Moro, Oreg., Lind, Wash., and Nephi, Utah, for stated years*

Month	Average precipitation (inches)			Month	Average precipitation (inches)		
	Moro, 1910–1929	Lind, 1916–1930	Nephi, 1898–1929		Moro, 1910–1929	Lind, 1916–1930	Nephi, 1898–1929
January	1.63	0.85	1.09	August	0.23	0.32	0.93
February	1.28	.70	1.19	September	.88	.59	.91
March	.77	.49	1.53	October	.83	.52	1.15
April	.76	.62	1.33	November	1.80	1.22	.90
May	.88	.61	1.56	December	1.65	1.08	1.02
June	.55	.71	.57				
July	.20	.11	.84	Total	11.46	7.82	13.02

During the period of the experiments Nephi had the highest annual precipitation and Lind the lowest. More of the precipitation at Nephi was in the form of snow, although there was always some snow at Moro and at Lind. In case of a sudden thaw with frozen soil, a part of the winter precipitation at Moro and Lind sometimes is lost as run-off on account of the rolling topography of the land.

The average rainfall for April, May, and June at Lind was 1.94 inches, or nearly 25.0 per cent of the annual precipitation. At Moro the average rainfall for these three months was 2.19 inches, or 19.1 per cent of the annual precipitation. At Nephi the average rainfall for these months was 3.46 inches, or 26.6 per cent of the annual precipitation.

EVAPORATION

A record of the evaporation from a free water surface was kept. At Nephi this record was kept since 1908, at Moro since 1911, and at Lind since 1922. Table 3 shows the average evaporation from a free water surface at each of the three stations.

TABLE 3.—*Average monthly evaporation from a free water surface for the six months from April to September, inclusive, at Moro, Oreg., Nephi, Utah, and Lind, Wash., for stated years*

Month	Average evaporation (inches)			Month	Average evaporation (inches)		
	Moro, 1911–1929	Nephi, 1908–1929	Lind, 1922–1930		Moro, 1911–1929	Nephi, 1908–1929	Lind, 1922–1930
April	4.62	3.90	5.25	August	8.68	8.73	8.83
May	6.57	6.54	7.56	September	5.03	6.36	5.36
June	8.26	8.73	8.30				
July	10.25	9.55	10.73	Total	43.41	43.81	46.03

TEMPERATURE

Table 4 shows the mean monthly temperatures at Moro for a 19-year period, at Nephi for a 22-year period, and at Lind for a 10-year period. At Nephi temperatures are recorded only from April 1 to November 1 of each year. Temperature records at Lind are available only for the last 10 years of these experiments, but temperatures for a former period, taken from United States Weather Bureau records kept in the same form, show similar range.

TABLE 4.—*Average mean temperatures, by months, at Moro, Oreg., Lind, Wash., and Nephi, Utah*

Month	Average mean temperature (° F.)			Month	Average mean temperature (° F.)		
	Moro, 1911–1929	Lind, 1920–1930[1]	Nephi, 1908–1929		Moro, 1911–1929	Lind, 1920–1930[1]	Nephi, 1908–1929
January	29.8	25.5	----------	July	68.5	72.8	71.0
February	33.9	33.0	----------	August	67.5	70.8	69.6
March	41.8	41.6	----------	September	57.3	60.1	61.0
April	47.3	49.0	44.4	October	49.5	51.7	48.0
May	54.1	56.5	53.6	November	38.6	37.7	----------
June	61.6	65.5	63.5	December	31.0	29.1	----------

[1] 10 years from Sept. 1, 1920, to Aug. 31, 1930.

The average frost-free period at each station is shown in Table 5. Frosts in the late spring or early autumn rarely damage the wheat crop at these stations, though severe winter temperatures sometimes may cause winterkilling of fall-sown grain. During the period for which data are available the latest spring frost recorded at Lind was on June 8 in 1901 and the earliest autumn frost on September 12 in 1921. The latest frost in the spring recorded at Moro was on June 1, 1917; the earliest autumn frost was on September 3 in 1912. The latest spring frost at Nephi was on July 2 in 1921 and the earliest autumn frost on September 4 in 1912.

TABLE 5.—*Frost-free period at Moro, Oreg., Lind, Wash., and Nephi, Utah, for stated years*

Year	Lind	Moro	Nephi	Year	Lind	Moro	Nephi
	Days	*Days*	*Days*		*Days*	*Days*	*Days*
1910			142	1921	108	107	81
1911		162	113	1922		155	126
1912		127	96	1923		146	87
1913		171	143	1924	156	152	153
1914		108	96	1925	164	172	112
1915		211	93	1926	122	116	136
1916		144	108	1927	139	142	126
1917		137	105	1928	162	162	88
1918		158	100	1929	157	157	120
1919		135	112				
1920		136	115	Average	144	147	113

TILLAGE EXPERIMENTS

TREATMENT OF LAND BEFORE PLOWING

All the land at the stations at Moro and Lind was in crop at the time these stations were established. No experiments, therefore, have been conducted at either station on the best methods of preparing sod ground for wheat. At Nephi the station was located on virgin land.

After removing a grain crop the farmer may do one of several things to his fields. He may (1) disk the stubble land in the fall, (2) burn the stubble in the fall or spring, (3) plow the land in the fall, (4) leave the stubble standing during the winter and disk the land in the spring, or (5) leave the land uncultivated until it is plowed in the spring. Each of these practices is followed by farmers in Oregon, Washington, Idaho, and Utah. Plowing for fallow usually is done in the spring by most farmers in these States.

FALL DISKING

Experiments have been conducted at each of the three stations to determine the value of fall disking when the land is to be spring plowed. These results are summarized in Table 6 and are shown graphically in Figure 9. The acre yields reported in this table are based on yields of single tenth-acre plots at Moro and Nephi and single twentieth-acre plots at Lind.

Advantages claimed for fall disking are: (1) It kills weeds that may take out moisture after harvest, (2) it permits better penetration of the autumn and winter precipitation by mellowing the surface soil, (3) it covers weed seeds and shattered grain so that they germinate more quickly, (4) it prevents run-off in the early spring, and (5) it hastens the decay of the stubble and other vegetation.

Experiments at the three stations have proved that these advantages are apparent rather than real. Table 6 shows that fall disking slightly reduced yields at Moro, Nephi, and Lind. Double-disking ordinarily will not kill Russian thistle, one of the troublesome weeds that grow on wheatland after harvest. The moisture determinations at these stations also have shown that disking the stubble land in the fall does not aid in absorption of the autumn and winter precipitation. It more frequently deters moisture penetration by creating a mulch which holds the moisture near the surface and thereby hastens its

escape by evaporation. This is especially true if the disking is done when the ground is dry. The standing stubble during the winter is no doubt a factor in increasing soil moisture, as it helps to hold snow where it falls and prevents drifting to a considerable extent.

As is shown later, spring disking of the stubble generally proved beneficial if the plowing was done very late in the spring. Fall disk-

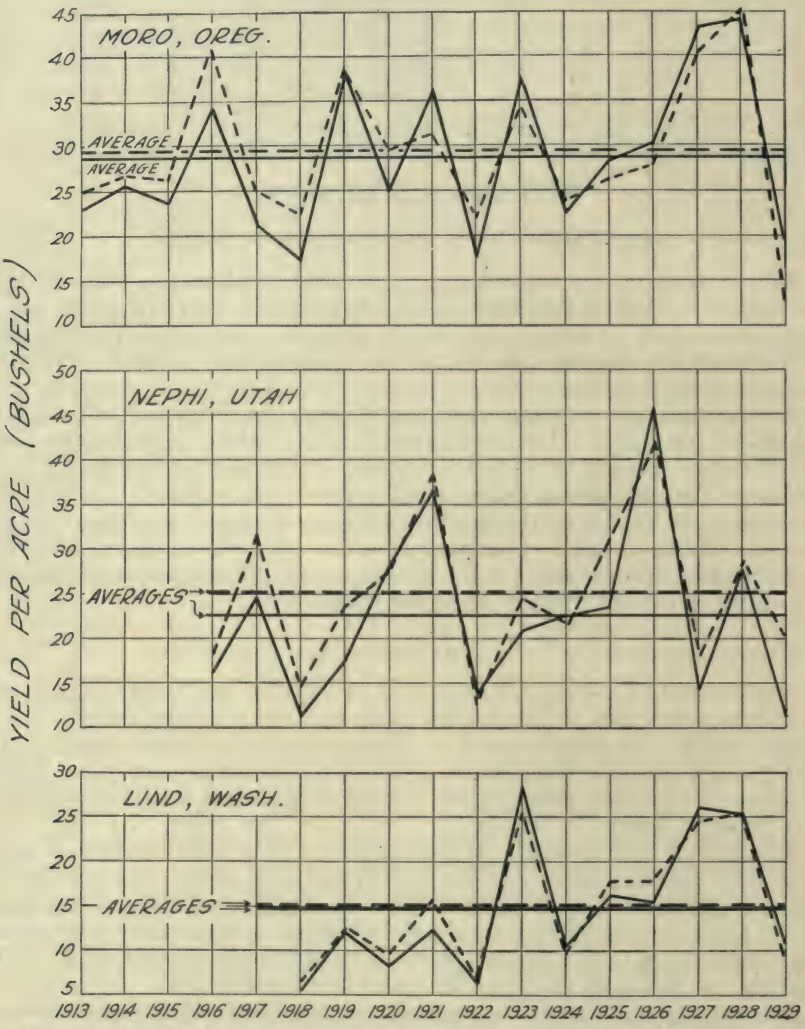


FIGURE 9.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., Nephi, Utah, and Lind, Wash., when grown after summer fallow for which the ground had been plowed in early spring with the stubble disked (solid lines) or not disked (broken lines) in the previous fall

ing, however, is not a satisfactory substitute for spring disking, because weeds and volunteer grain normally do not get started early enough in the autumn to be destroyed by fall disking. A good double disking in the spring ordinarily will kill all plant growth, which is the chief value of disking.

TABLE 6.—*Annual and average yields of Turkey winter wheat on land disked in the fall and plowed early in the following spring for fallow and on land plowed in the spring but not disked in the fall, at Moro, Oreg., Lind, Wash., and Nephi, Utah, in varying periods from 1913 to 1929*

Station and treatment	Acre yield (bushels)																	
	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
Moro, Oreg.:																		
Disked in the fall	23.0	25.6	23.6	34.3	21.2	17.3	38.3	25.0	36.5	17.3	37.3	22.7	28.3	30.3	43.1	44.2	18.7	28.6
Not disked in the fall	25.1	26.9	26.3	41.3	25.0	22.3	38.5	29.7	31.3	22.0	34.7	23.7	26.2	28.0	40.5	45.2	12.7	29.4
Lind, Wash.:																		
Disked in the fall						5.6	12.2	8.3	12.3	6.1	28.6	10.7	16.2	15.7	26.0	25.5	10.8	14.8
Not disked in the fall						6.2	12.3	9.8	15.7	6.6	26.2	9.8	17.7	18.0	24.7	25.5	9.2	15.1
Nephi, Utah:																		
Disked in the fall, fall plowed				18.0	25.7	15.8	20.8	30.5	40.2	15.5	20.7	22.8	28.7	51.5	16.3	26.2	15.7	24.9
Disked in the fall, spring plowed				16.0	24.7	11.2	17.3	28.0	36.9	13.8	21.0	22.8	23.7	45.8	14.5	27.8	11.3	22.5
Not disked, spring plowed				18.3	31.8	14.5	23.7	27.5	38.4	12.8	24.5	21.7	30.4	42.0	17.0	28.8	20.0	25.1
Not disked, fall plowed				19.3	27.8	16.2	19.3	27.1	48.0	15.7	23.0	23.8	30.2	52.7	18.5	26.8	16.8	26.1

SPRING DISKING

Experiments to determine the value of disking in the spring prior to plowing also were conducted at Moro and Lind. The results

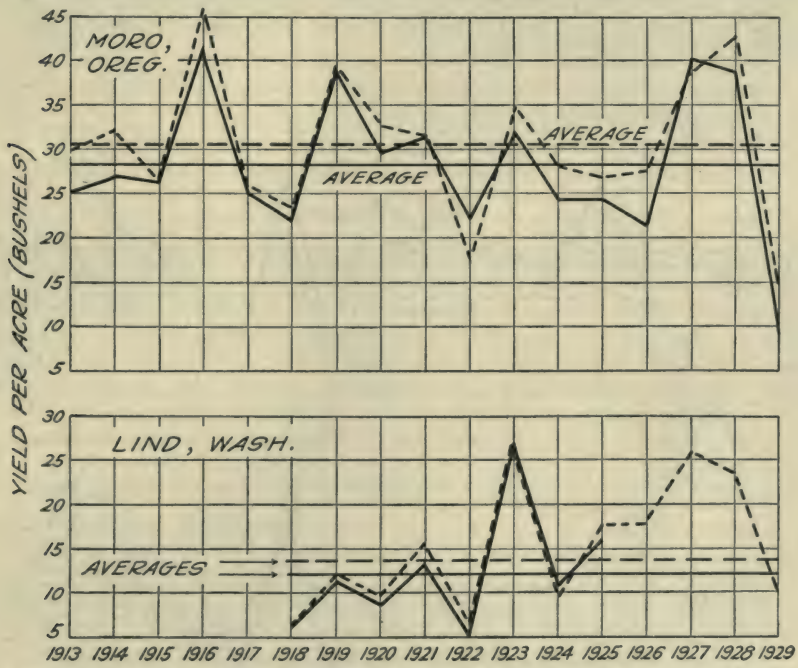


FIGURE 10.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., and Lind, Wash., when grown after summer fallow for which the ground had been plowed in early spring with the stubble disked (solid lines) or not disked (broken lines) in early spring before plowing

obtained from these experiments are presented in Table 7 and are shown graphically in Figures 10, 11, and 12. It will be noted from

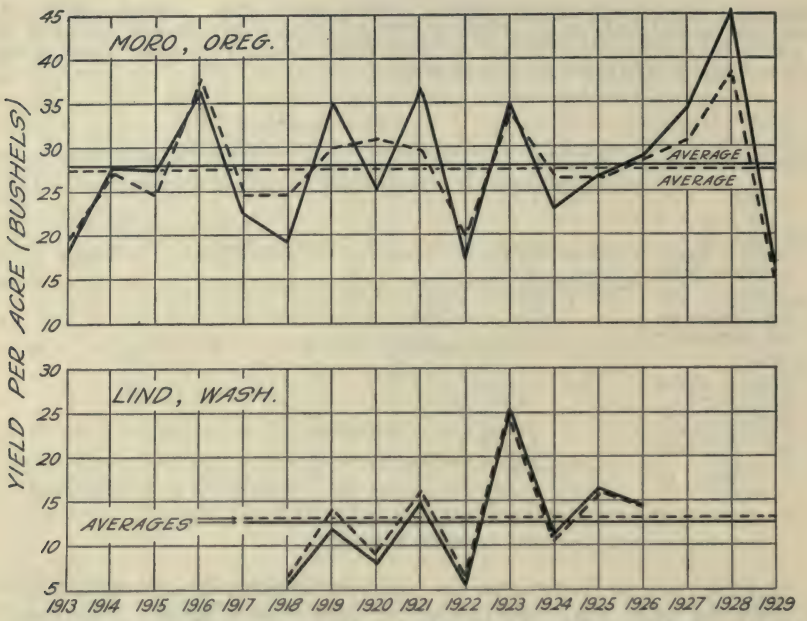


FIGURE 11.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., and Lind, Wash., when grown after summer fallow for which the ground had been plowed in late spring with the stubble disked (solid lines) or not disked (broken lines) in early spring before plowing

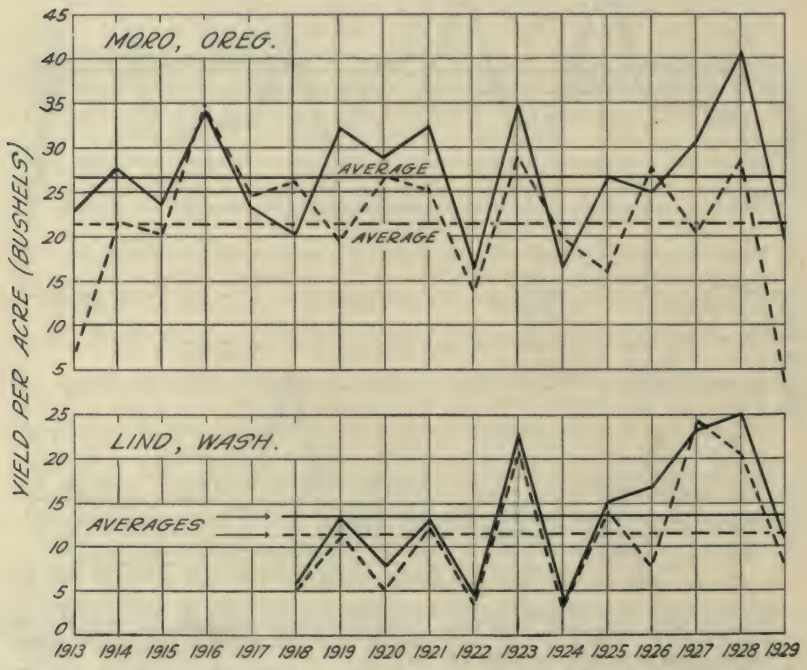


FIGURE 12.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., and Lind, Wash., when grown after summer fallow for which the ground had been plowed in early summer with the stubble disked (solid lines) or not disked (broken lines) in early spring before plowing

this table that spring disking has increased wheat yields at both Moro and Lind when the plowing was done as late as June 1. With plowing done in April and early in May there seems to be no advantage in spring disking.

TABLE 7.—*Annual and average yields of Turkey winter wheat on land disked and not disked before plowing at different times in the spring at Moro, Oreg., 1913–1929, and at Lind, Wash., 1918–1929*

Station, date of plowing, and treatment before plowing	Acre yield (bushels)																	
	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
MORO, OREG.																		
Plowed early in April:																		
Disked	25.1	26.9	26.3	41.3	25.0	22.3	38.5	29.7	31.3	22.0	32.0	24.2	24.3	21.5	40.2	38.8	9.2	28.2
Not disked	30.0	32.0	26.4	45.7	25.7	23.5	39.7	32.8	31.7	17.5	34.7	28.0	27.0	27.5	39.0	42.8	14.7	30.5
Plowed early in May:																		
Disked	18.5	27.8	27.5	35.1	22.3	19.2	35.3	25.3	36.7	17.0	35.2	23.0	26.8	29.0	34.7	45.5	16.5	28.0
Not disked	19.0	27.0	24.7	38.0	24.7	24.7	30.0	31.0	29.8	20.0	34.0	26.8	25.5	27.5	30.8	39.0	14.2	27.5
Plowed early in June:																		
Disked	23.0	27.7	23.9	34.3	23.1	20.3	32.3	29.0	32.5	16.5	34.7	16.3	26.8	25.0	30.7	40.8	19.5	26.8
Not disked	7.3	21.6	20.5	34.8	24.7	26.0	19.5	26.5	25.2	13.7	29.0	19.8	16.0	27.5	20.3	28.7	3.3	21.4
LIND, WASH.																		
Plowed early in March:																		
Disked						6.1	11.2	8.7	13.3	5.1	27.2	10.7	16.0					12.3
Not disked						6.2	12.3	9.8	15.7	6.6	26.2	9.8	17.7	18.0	25.5	23.8	9.8	15.1
Plowed in mid-April:																		
Disked						5.9	12.0	8.1	15.0	5.6	25.7	11.1	16.5	14.7				12.7
Not disked						6.0	14.2	9.2	16.3	5.8	25.5	10.5	16.0	14.2				13.1
Plowed early in June:																		
Disked twice (Mar. 1, Apr. 10)						5.9	14.3	9.2	12.7	5.1	26.0	8.7	15.2	13.7	25.8	28.3	10.3	14.6
Disked once (Mar. 1)						5.8	13.3	8.0	13.0	5.5	23.0	3.7	15.2	16.8	23.2	25.0	10.5	13.6
Not disked						5.3	11.3	5.0	12.3	3.6	21.3	3.3	14.0	7.8	24.2	20.2	7.5	11.3

BURNING STUBBLE

In certain sections of heavy rainfall in the eastern parts of Oregon and Washington the practice of burning the stubble before plowing is quite generally followed by farmers. The stubble usually is burned in the early spring, though some farmers burn it late in the fall. When wheat is harvested with the combined harvester, as is the custom in eastern Oregon and eastern Washington, a large part of the crop growth is left on the land in the form of stubble. Most of the straw that goes through the machine also is left in the field in windrows or piles, to be burned or plowed under. Frequently the stubble and straw are so heavy that much difficulty is experienced in cultivating fallow after they are turned under.

Experimental data to determine the actual effect on the yield of wheat of burning the stubble are available at the Nephi Substation, where this experiment has been in progress during the 14 years from 1916 to 1929, inclusive, and at Moro for the 7 years from 1923 to 1929, inclusive. The data are shown in Table 8.

TABLE 8.—*Annual and average yields of wheat on fallow with stubble variously treated at Nephi, Utah, and at Moro, Oreg., for stated years*

Station and treatment after plowing	Acre yield (bushels)														
	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
NEPHI, UTAH															
Ordinary treatment, fall plowed	20.0	23.6	17.4	21.9	25.5	38.9	14.1	21.0	17.6	29.7	44.0	15.2	20.9	18.3	23.4
All straw plowed under	11.1	22.7	20.2	20.7	28.6	39.2	14.2	19.2	20.4	30.4	44.9	16.0	22.0	19.1	23.5
All straw burned on plot	12.6	24.4	20.5	21.7	29.0	40.8	16.3	22.0	20.2	30.3	46.1	17.6	24.9	18.7	24.7
Grain headed high:															
Stubble plowed under	10.8	25.6	18.2	23.4	27.6	40.9	14.7	21.3	19.7	32.7	48.3	17.1	22.8	20.1	24.5
Stubble burned	10.9	26.1	17.1	25.3	26.1	42.7	15.1	25.0	19.8	32.7	49.3	18.3	24.2	21.1	25.3
MORO, OREG.															
Binder stubble turned under	----	----	----	----	----	----	----	29.5	11.7	29.0	20.7	36.1	32.8	13.0	24.7
All straw turned under	----	----	----	----	----	----	----	31.9	14.6	27.0	26.1	37.9	32.4	14.5	26.3
All straw burned	----	----	----	----	----	----	----	31.3	10.3	26.0	23.2	36.5	32.3	12.5	24.6

At Nephi a slightly higher average yield was obtained from the plots on which the stubble was burned, while at Moro the highest average yield was obtained from the plots with all straw returned and plowed under. While the results from these experiments are not conclusive, the deficiency of humus in the dry-farm soils of the Columbia River and Great Basin regions suggests the advisability of turning under the stubble and straw whenever possible in preference to burning them. To turn under heavy stubble properly, jointers should be used on the plow; and when the total straw is to be turned under, a straw spreader should be used on the combine. Disking prior to plowing also aids in more completely turning under straw and stubble.

PLOWING

Of the controllable factors influencing yields of winter wheat, the time of plowing has been found to be one of the most important. Time of plowing also is of much importance to the dry farmer in the distribution of labor. Plowing for summer fallow may be done in the fall at any time after harvest until the ground freezes or at any time in the spring after the soil is dry enough. In many sections of eastern Oregon and Washington the harvesting of wheat is completed by August 15, while the ground does not often freeze before December 1. This allows a considerable period for fall plowing, both before and after the time for sowing winter wheat. Spring plowing, however, is generally practiced by farmers in the Columbia River and Great Basin areas.

Experiments to determine the best time to plow as well as the best manner of plowing were carried on at each of the three stations, and the results are presented in the following pages.

PLAN OF EXPERIMENTS AT MORO

In the experiments to determine the best date for spring plowing at Moro, 60 tenth-acre plots were used, 30 being in crop and 30 in fallow each year. Of these plots 2 out of every 10 were check plots.

One series of 10 plots was plowed on April 1, one on May 1, and one on June 1, except that the check plots in each series were plowed on April 1. Different methods of cultivating the summer fallow were employed on each of the plots in a series, except that all check plots were treated alike.

For the fall-plowing experiments, 40 tenth-acre plots were used, 20 being in crop and 20 left fallow each year. Eight plots were plowed early in the fall when the ground was dry, 4 with a disk plow and 4 with a moldboard plow. Eight plots were plowed late in the fall when the ground was wet, 4 with a disk plow and 4 with a moldboard. Beginning in the fall of 1919 all fall plowing was done with a moldboard plow. Two plots out of every 10 were check plots uniformly cultivated. During the first five years these were plowed late in the fall with a moldboard plow, but since then they have been plowed on April 1 with a moldboard plow, so as to have them uniform with the check plots in the experiments to determine the best date to plow in the spring.

In all the date-of-plowing experiments, Turkey winter wheat was used. The depth of plowing was from 7 to 8 inches in both spring and fall plowing.

Depth-of-plowing experiments also have been conducted at Moro since 1912. In these experiments 40 tenth-acre plots were used, 20 being cropped and 20 left fallow each year. One series of 10 plots was plowed from 8 to 10 inches deep and one series from 4 to 5 inches deep each year. Pacific Bluestem spring wheat was grown until 1917; in 1918 and 1919 Baart spring wheat was grown; and from 1920 to 1929, inclusive, Turkey winter wheat was grown. In each series two check plots were plowed 8 to 10 inches deep, uniformly cultivated, and cropped to spring wheat from 1912 to 1919, inclusive, and to winter wheat from 1920 to 1929, inclusive.

The plots of the tillage experiments were arranged in series of 10, with the third and eighth plots in each series used as uniformly cultivated check plots. The dimensions of the plots were 2 by 8 rods. Each series or block was surrounded by a road 16 feet wide, and the plots were divided by alleys 4½ feet wide. In the spring-plowing experiments the check plots were plowed in April and given uniform cultural treatment thereafter. In the fall-plowing experiments the check plots were plowed late in the fall during the first five years, but after 1919 they were plowed in the spring to make them uniform with the other check plots.

YIELDS OF CHECK PLOTS AT MORO

The average yields of the check plots in the date-of-plowing experiments at Moro are shown in Table 9. The yields from the check plots are average yields of two plots in each year. Average yields are shown in the table for the entire 17-year period from 1913 to 1929, inclusive; for the years 1914 to 1929, inclusive; and for 1920 to 1929, inclusive. The yields of the check plots will be taken into consideration in interpreting the results obtained in the tillage experiments at Moro.

129784°—32——2

TABLE 9.—*Average yields of Turkey winter wheat on the uniformly cultivated check plots in the tillage experiments at Moro, Oreg., by periods in all or part of the 17-year period 1913–1929*

Series	Acre yield (bushels)			Series	Acre yield (bushels)		
	1913–1929	1914–1929	1920–1929		1913–1929	1914–1929	1920–1929
April plowing	29.3	29.4	28.7	Late fall plowing (wet)	-------	28.0	29.2
May plowing	29.1	29.5	28.6	Shallow spring plowing	-------	-------	26.2
June plowing	27.7	27.9	28.1	Deep spring plowing	-------	-------	24.7
Early fall plowing (dry)	-------	30.4	30.8				

DATE-OF-PLOWING EXPERIMENTS

RESULTS AT MORO

The yields obtained in the date-of-plowing experiments in the years 1913 to 1929, inclusive, are shown in Table 10 for various

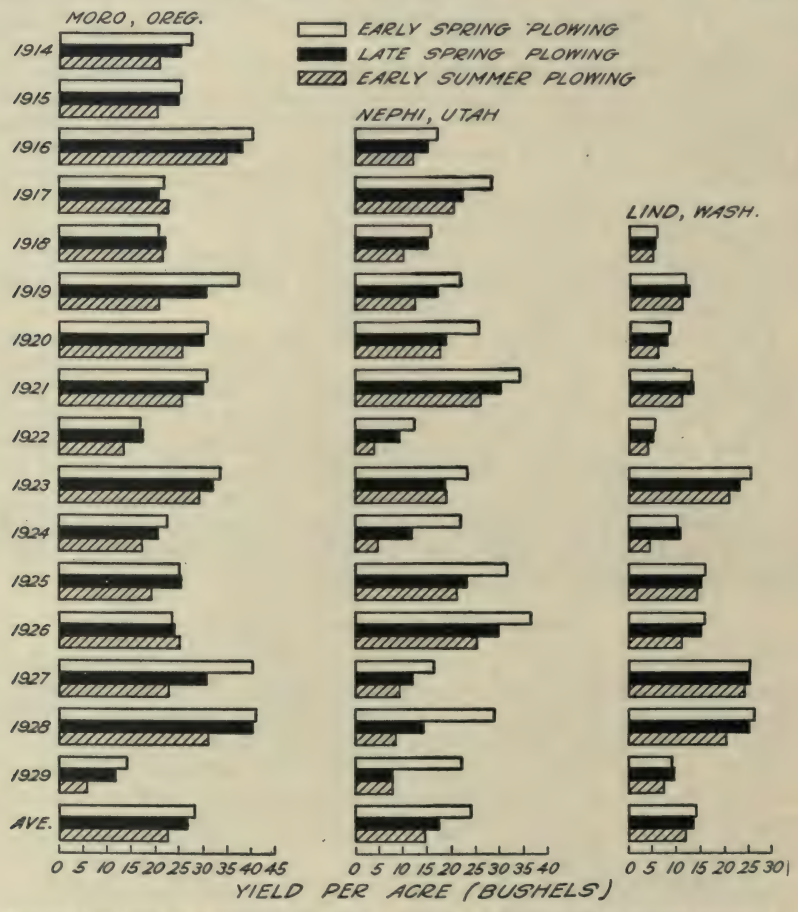


FIGURE 13.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., Nephi, Utah, and Lind, Wash., when grown after summer fallow for which the land had been plowed in early spring, late spring, and early summer, respectively

methods of cultivating the summer fallow. For the spring plowing the yields are from single tenth-acre plots. In the fall-plowing experiments the yields are averages of duplicate tenth-acre plots for each year. For each date of plowing eight tenth-acre plots were used in addition to the check plots. Results are available in the spring-plowing experiments for the 17 years from 1913 to 1929, inclusive, and in the fall-plowing experiments for the 16 years from

FIGURE 14.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., Nephi, Utah, and Lind, Wash., when grown after summer fallow for which the land had been plowed early in the fall (dry), late in the fall (wet), and early in the spring, respectively

1914 to 1929, inclusive. Data from these experiments are shown graphically in Figures 13 and 14. Figures 15 and 16 show growth of weeds and volunteer wheat on the late spring and early summer plowing dates at Moro, Oreg., and Lind, Wash. Figures 17 to 19, inclusive, show differences in stand and growth of winter wheat sown on early and late plowed fallow at Lind, Wash., and Moro, Oreg.

FIGURE 15.—Growth of weeds and volunteer wheat on an uncultivated plot on May 1, 1931, at Moro, Oreg., and on an adjacent plot which had been disked in the early spring

FIGURE 16.—Growth of volunteer Turkey winter wheat at time of June plowing in 1927 at Lind, Wash.

FIGURE 17.—Turkey winter wheat on early spring plowing at Lind, Wash. This plot was sown September 28, 1923, and photographed June 21, 1924. It yielded at the rate of 11.5 bushels per acre. Because of early spring plowing, the seed bed was in good condition after the first autumn rains. Compare with Figure 18

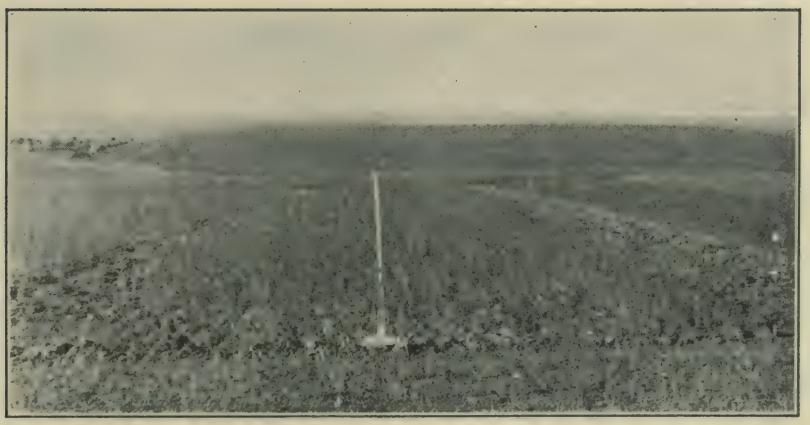


FIGURE 18.—Turkey winter wheat on late spring plowing at Lind, Wash. On account of soil being dry when plowed, the first fall rains failed to put the seed bed in good condition. Photographed June 21, 1924. This plot yielded at the rate of 3.3 bushels per acre. Compare with Figure 17

FIGURE 19.—Turkey winter wheat at Moro, Oreg., on late spring-plowed fallow (left) and on early spring-plowed fallow (right). Note thinner stand and less thrifty growth of plants on plot plowed late in the spring for fallow

TABLE 10.—*Annual and average yields of Turkey winter wheat in tillage experiments at Moro, Oreg., during the 17-year period, 1913–1929*

[Yields of check plots are not included in the averages]

Method of cultivating fallow	Acre yield (bushels)																		
	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	17-year average (1913–1929)	16-year average (1914–1929)
Plowed April 1 (early spring):																			
Treatment 1	23.0	25.6	23.6	34.3	21.2	17.3	38.3	25.0	36.5	17.3	37.3	22.7	28.3	30.3	43.1	44.2	18.7	28.6	29.0
Treatment 2	22.3	26.0	22.1	33.2	24.0	21.0	36.2	27.0	27.7	16.3	32.0	20.2	23.3	18.7	41.2	35.7	10.5	25.7	25.9
Treatment 3 (check)	25.1	26.9	26.3	41.3	25.0	22.3	38.5	29.7	31.3	22.0	32.0	24.2	24.3	21.5	40.2	38.8	9.2	28.2	28.3
Treatment 4	27.1	29.3	24.8	39.8	19.8	19.5	31.2	27.7	25.8	15.8	33.0	22.3	23.7	19.0	40.0	41.0	13.8	26.7	26.7
Treatment 5	30.0	32.0	26.4	45.7	25.7	23.5	39.7	32.8	31.7	17.5	34.7	28.0	27.0	27.5	39.0	42.8	14.7	30.5	30.5
Treatment 6	23.7	30.5	27.5	37.8	22.0	20.3	41.2	35.0	32.8	19.3	33.8	25.5	26.3	24.2	36.5	42.8	15.5	29.1	29.4
Treatment 7	27.2	31.0	25.8	44.1	14.7	18.3	36.0	33.3	25.7	16.2	30.7	22.5	21.8	19.7	40.3	46.8	17.5	27.7	[1]27.8
Treatment 8 (check)	26.3	28.3	27.9	45.7	23.5	21.7	40.2	37.3	34.2	18.2	34.7	23.7	26.2	28.0	40.5	45.2	12.7	30.3	30.5
Treatment 9	23.1	28.5	28.1	42.7	25.7	22.8	39.2	34.5	35.7	18.5	36.0	27.2	27.8	30.2	39.7	44.2	16.5	30.6	31.1
Treatment 10	18.0	28.0	28.7	49.3	25.1	27.8	38.5	38.3	35.8	19.8	35.0	15.7	24.3	22.2	44.0	36.0	8.2	29.1	29.8
Average	24.3	28.9	25.9	40.9	22.3	21.3	37.5	31.7	31.5	17.6	34.1	23.0	25.3	24.0	40.5	41.7	14.4	28.5	28.8
Plowed May 1 (late spring):																			
Treatment 1	18.5	27.8	27.5	35.1	22.3	19.2	35.3	25.3	36.7	17.0	35.2	23.0	26.8	29.0	34.7	45.5	16.5	28.0	28.6
Treatment 2	20.5	25.0	22.7	33.2	23.2	22.3	28.5	28.3	29.8	17.5	28.3	17.0	24.0	20.7	30.7	38.2	11.7	24.8	25.1
Treatment 3 (check)	23.6	27.4	27.0	38.2	24.3	22.0	37.2	28.3	35.8	19.8	30.5	24.3	25.5	23.8	35.8	42.8	7.3	27.9	28.1
Treatment 4	19.8	28.0	25.1	36.7	19.0	23.5	30.3	27.7	26.0	17.0	31.7	16.5	26.3	19.0	30.3	40.5	13.7	25.4	25.7
Treatment 5	19.0	27.0	24.7	38.0	24.7	24.7	30.0	31.0	29.8	20.0	34.0	26.8	25.5	27.5	30.8	39.0	14.2	27.5	28.0
Treatment 6	16.0	26.3	25.5	40.2	20.3	19.5	31.8	31.5	30.3	19.0	32.7	25.7	26.5	25.7	27.3	39.8	15.5	26.7	27.4
Treatment 7	18.3	27.7	25.5	35.8	10.3	24.1	30.5	32.3	28.8	15.8	32.8	17.5	25.2	21.7	33.5	42.8	9.8	25.4	[1]25.9
Treatment 8 (check)	21.8	28.2	30.0	46.3	25.4	23.5	42.5	38.5	36.0	20.5	34.3	22.8	28.7	26.7	35.3	45.0	9.2	30.3	30.8
Treatment 9	17.7	23.4	26.4	42.8	25.4	24.0	32.8	31.8	31.2	17.7	34.7	26.7	27.2	30.3	31.5	42.8	11.0	28.1	28.7
Treatment 10	18.1	20.8	24.6	48.0	25.8	22.7	30.7	35.0	31.8	18.2	30.8	14.8	22.8	22.7	30.0	38.0	6.7	26.0	26.5
Average	18.5	25.8	25.3	38.7	21.4	22.5	31.2	30.4	30.6	17.8	32.5	21.0	25.5	24.6	31.1	40.8	12.4	26.5	27.0

See footnote end of table.

TABLE 10.—*Annual and average yields of Turkey winter wheat in tillage experiments at Moro, Oreg., during the 17-year period, 1913–1929*—Continued

[Yields of check plots are not included in the averages]

Method of cultivating fallow	Acre yield (bushels)																		
	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	17-year average (1913–1929)	16-year average (1914–1929)
Plowed June 1 (early summer):																			
Treatment 1	23.0	27.7	23.9	34.3	23.1	20.3	32.3	29.0	32.5	16.5	34.7	16.3	26.8	25.0	30.7	40.8	19.5	26.8	27.1
Treatment 2	7.4	22.1	21.5	36.2	24.8	23.0	19.8	24.2	23.0	12.3	30.2	17.7	18.8	23.0	25.2	31.3	5.3	21.5	22.4
Treatment 3 (check)	23.0	25.7	26.5	32.0	25.0	21.2	35.8	27.7	37.5	19.3	29.5	21.3	26.7	23.2	37.7	40.2	6.2	27.0	27.2
Treatment 4	7.2	24.0	21.3	36.8	22.5	22.7	19.8	25.0	24.0	12.3	28.5	18.2	19.2	25.7	23.7	31.2	5.3	21.6	22.5
Treatment 5	7.3	21.6	20.5	34.8	24.7	26.0	19.5	26.5	25.2	13.7	29.0	19.8	16.0	27.5	20.3	28.7	3.3	21.4	22.3
Treatment 6	10.8	21.3	21.5	36.3	20.8	18.2	23.0	26.0	27.3	15.2	30.3	19.8	18.0	25.0	19.7	29.5	4.8	21.6	22.3
Treatment 7	6.5	18.5	20.8	34.2	20.6	26.1	19.8	28.5	27.1	15.0	31.1	15.0	17.0	29.8	20.3	30.3	3.7	21.4	[1] 22.4
Treatment 8 (check)	26.0	27.2	25.0	32.0	23.3	20.3	37.8	37.0	38.2	19.7	34.5	22.5	26.3	29.3	35.1	41.3	8.0	28.4	28.6
Treatment 9	10.5	19.0	19.5	32.3	24.3	20.0	21.3	23.5	24.7	14.5	30.3	17.5	18.7	29.3	22.5	31.0	5.0	21.4	22.1
Treatment 10	11.9	18.0	22.1	36.2	24.3	19.5	19.3	26.3	24.2	13.5	24.1	18.8	21.7	21.3	24.0	31.2	3.2	21.2	21.7
Average	10.6	21.5	21.4	35.1	23.1	22.0	21.9	26.1	26.0	14.1	29.8	17.9	19.5	25.8	23.3	31.8	6.3	22.1	22.9
Plowed in early fall (dry):																			
Treatment 1		23.5	25.5	34.7	20.0	18.3	30.5	28.6	39.6	18.0	33.1	15.5	20.1	22.6	35.0	39.5	17.2		26.4
Treatment 3 (check)		25.9	24.0	43.7	21.4	24.4	38.2	33.9	42.8	18.5	34.4	24.9	26.0	26.0	38.1	39.7	24.0		30.4
Treatment 4		22.9	18.1	35.3	20.7	18.0	28.8	20.6	34.5	18.0	29.1	15.2	20.0	16.0	28.6	40.7	14.7		23.8
Treatment 5		24.1	24.4	42.9	21.3	21.3	32.4	30.7	38.8	17.0	32.9	19.2	21.3	22.6	37.5	42.0	21.2		28.1
Treatment 6		24.4	22.6	36.8	20.5	17.9	35.7	28.6	38.4	17.0	32.9	19.3	21.8	22.4	35.4	39.8	15.5		26.8
Average		23.7	22.7	37.4	20.6	18.9	31.9	27.1	37.8	17.5	32.0	17.3	20.8	20.9	34.1	40.5	17.2		26.3
Plowed in late fall (wet):																			
Treatment 1		21.2	23.9	30.5	20.6	16.6	31.7	26.6	40.6	17.0	32.8	11.7	21.4	20.7	36.5	40.2	16.0		25.5
Treatment 3 (check)		25.0	21.8	32.1	21.3	21.5	35.8	29.4	40.1	17.5	32.0	22.1	27.2	23.8	37.9	40.5	22.5		28.2
Treatment 4		19.5	22.0	34.6	18.2	16.6	32.8	25.7	40.0	14.4	32.7	15.6	18.2	17.4	28.6	46.5	20.8		25.2
Treatment 5		22.8	21.4	31.2	21.8	18.3	31.9	25.2	37.7	15.0	31.7	10.4	22.9	21.9	35.5	37.8	18.7		25.3
Treatment 6		21.2	22.5	28.6	20.6	15.7	32.8	23.7	38.7	15.5	31.3	9.6	21.9	18.9	33.5	35.8	19.5		24.4
Average		21.2	22.5	31.2	20.3	16.8	32.3	25.3	39.3	15.5	32.1	11.8	21.1	19.7	33.5	40.1	18.8		25.1

[1] Treatment 7 was changed in 1928 to delayed cultivation of fallow, with no packing.

Table 11 summarizes the data given in Table 10 and in addition shows the yields of winter wheat obtained in the years from 1914 to 1929, inclusive, after summer fallow plowed in the fall with a disk plow and with a moldboard plow. The use of the disk plow was discontinued after 1919. In Table 11 the annual yields from the fall-plowed plots are from four tenth-acre plots each year until 1920. Since 1920 the yields are averages of eight tenth-acre plots each year.

TABLE 11.—*Annual and average yields of Turkey winter wheat on fallow land plowed on different dates at Moro, Oreg., during the 16-year period, 1914–1929*

Method and time of plowing	Acre yield (bushels)																
	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
Fall plowing:																	
Disk plow—																	
Early (dry)	23.3	22.4	33.9	19.0	17.6	30.9	----	----	----	----	----	----	----	----	----	----	----
Late (wet)	21.0	23.2	30.4	20.2	16.3	31.3	----	----	----	----	----	----	----	----	----	----	----
Moldboard plow—																	
Early (dry)	24.1	22.9	41.0	22.2	20.1	32.8	27.1	37.8	17.5	32.0	17.3	20.8	20.9	34.1	40.5	17.2	26.3
Late (wet)	21.3	21.6	32.1	20.3	17.2	33.2	25.3	39.3	15.5	32.1	11.8	21.1	19.7	33.5	40.1	18.8	25.1
Spring plowing:																	
Plowed April 1	28.9	25.9	40.9	22.3	21.3	37.5	31.7	31.5	17.6	34.1	23.0	25.3	24.0	40.5	41.7	14.4	28.8
Plowed May 1	25.8	25.3	38.7	21.4	22.5	31.2	30.4	30.6	17.8	32.5	21.0	25.5	24.6	31.1	40.8	12.4	27.0
Summer plowing:																	
Plowed June 1	21.5	21.4	35.1	23.1	22.0	21.9	26.1	26.0	14.1	29.8	17.9	19.5	25.8	23.3	31.8	6.3	22.9

The methods of cultivation used on each of the 10 plots in the experiments reported in Table 10 were as follows:

1. Frequent cultivation; disked in both fall and spring before plowing; clean summer fallow.
2. No cultivation of summer fallow after plowing; weeds hoed off before maturity.
3 and 8. Check plots. Frequent cultivation; disked in the spring before plowing; clean fallow.
4. One harrowing immediately after plowing; no further cultivation; weeds hoed off before maturity.
5. Frequent cultivation; no disking before plowing; clean cultivation of fallow.
6. Frequent cultivation; same as No. 5 except that the crop was harrowed in the spring.
7. Packed with subsurface packer after plowing and harrowed once only; weeds hoed off before maturity.
9. Packed with subsurface packer and frequently cultivated; clean summer fallow.
10. Packed with surface packer and frequently cultivated; clean summer fallow.

Table 11 shows that the highest average yield of winter wheat was obtained from plowing for summer fallow on April 1, with the average yield from mid-spring plowing second by a slight margin over that from early fall plowing. The lowest average yields were obtained from the late fall and early summer plowing.

In the years 1914 to 1919, inclusive, when two types of plows were used for the fall-plowing experiments, the average yields obtained were as follows:

	Bushels per acre
Disk plow, early (dry)	24.5
Disk plow, late (wet)	23.7
Moldboard plow, early (dry)	27.2
Moldboard plow, late (wet)	24.3

These results indicate that for early fall plowing the moldboard plow was the better type. However, in considering the yields of the check plots, it appears that the ground on which was located the series of plots plowed early in the fall with the moldboard plow was slightly more productive than that on which was located the series plowed late in the fall.

The physical texture of the soil at Moro is such that when plowed dry in the fall with a moldboard plow it turns up in large lumps, so

that the ground is left very rough during the winter. This is not true of the late-fall plowing, which is done after the autumn rains have penetrated the soil sufficiently to make the ground plow easily and well. The disk plow, even when the ground is plowed dry, has a tendency to leave the surface finer and more even after plowing. The draft, of course, is much greater when the ground is plowed dry than when plowed wet.

The average yields obtained from the April plowing were higher than those obtained from either the May or the June plowing. The check-plot yields indicate that the productivity of the soil of the June-plowed series was not quite so great as that of the April-plowed and May-plowed series; but notwithstanding this, the yields obtained from the April-plowed series were significantly higher, especially when the fact is considered that they represent the average yields of eight tenth-acre plots each year.

The average acre yield of the April-plowed series in the 17-year period was 6.4 bushels per acre more than the average yield of the June-plowed series and 2 bushels more than the average yield of the May-plowed series.

In the 17 years for which results are available the yield from the June-plowed series slightly exceeded the average yield of the April-plowed series in the 3 years 1917, 1918, and 1926. In fact, during these three years the average yields of the series of plots plowed on all three dates varied but little. For the years 1913, 1919, 1927, and 1929, on the other hand, the average yield of the April-plowed series was nearly twice that of the June-plowed series.

The yields obtained from the plots plowed in the fall for summer fallow were lower than those obtained from the plots plowed early in the spring. The yield from fall plowing with the moldboard plow exceeded that from early spring plowing in only 2 years out of the 16. The 16-year average yield obtained from the plots plowed early (dry) in the fall was 2.5 bushels less than that obtained from the plots plowed on April 1 and 0.7 of a bushel less than the yield from the plots plowed on May 1

RESULTS AT LIND

The summer-fallow experiments at Lind were conducted on two series of twentieth-acre plots, one series being in fallow and one being in crop each year. These series of plots were widely separated, being located on opposite sides of the station farm. Check plots were not used from 1918 to 1923; and because the experiments were somewhat extensive and as originally outlined were considered temporary, they were not replicated. Beginning in 1924 the summer-fallow experiments were reoutlined and replotted each year until 1927, and check plots were then used to determine the uniformity of the plotted area.

In the Washington portion of the Columbia Basin the greater part of the fallow is plowed in the spring, only a very little being plowed in the fall. Two dates of fall plowing, two of spring plowing, and one of early summer plowing are included in these experiments. The two fall dates represent dry and wet plowing and the three spring and summer dates early, intermediate, and late work; the first being done at a time when the soil is wettest, the third when the soil is almost dry, and the second intermediate between the other two. All of

these dates vary with the season and are considered as more or less relative, depending on prevailing conditions during any one year. Experiments to determine the best date of plowing have been combined with those covering other factors as well, and the yields given for dates of plowing are the averages obtained from 3 to 12 plots plowed on each date in each year. The data are presented in Table 12.

TABLE 12.—*Annual and average yields of wheat on fallow land plowed on different dates at Lind, Wash., 1918–1930*

Time of plowing and condition of soil	Acre yield (bushels)													
	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
Fall plowing:														
Dry [1]	3.9	9.2	7.0	8.9	4.6	19.6	10.1	15.8	15.2	23.7	25.2	10.2	5.0	12.2
Wet [1]	4.1	9.6	7.5	11.7	4.9	20.5	10.1	15.7	15.7	24.0	26.8	10.0	5.5	12.8
Spring plowing:														
March (early) [2]	6.0	12.3	8.4	13.4	5.8	25.7	10.4	16.6	16.2	25.5	26.7	9.5	4.8	13.9
April (late) [3]	5.9	12.6	8.3	13.8	5.5	23.4	11.1	15.4	15.2	25.5	25.4	9.8	3.9	13.5
Summer plowing:														
June (early) [3]	5.7	11.1	6.6	11.3	4.7	21.6	4.9	14.8	11.6	24.7	20.4	7.7	4.6	11.5

[1] Average of 3 plots variously treated except in the period from 1924 to 1926 when single plots were used.
[2] Average of 12 plots variously treated.
[3] Average of 7 plots variously treated.

In planning the experiments it was intended to crop entirely to winter wheat, but seasonal conditions prevented adherence to this plan. For the crops of 1918, 1920, 1922, 1925, 1929, and 1930 the plots originally sown with Turkey winter wheat had to be resown with Baart spring wheat. This variation apparently did not affect the results, although all yields for the first three and the last of these years were low.

The variations in yields for the different dates of plowing given in Table 12 are not large and perhaps seem small when used as a basis for conclusions. The trends in variations, however, are very consistent from year to year; and because the percentage variations are comparable with those found under the more favorable conditions at the other stations, results from which are reported in this bulletin, the data presented should justify conclusions. The time and method of tillage are determined by local conditions, and, in the drier portions of the Columbia Basin, fall plowing, either wet or dry, is poor practice. The data given in Table 12 show this and are in full agreement with farm practice in this respect.

In the experiments on spring plowing the results show a decrease in yield with delay in date of plowing. The yields from the first two dates differ very little, but both are considerably better than those from the late or summer plowing. Before volunteer grain and weeds grow freely in the spring, there is no advantage from the moisture standpoint in stirring the soil. Moisture studies show that before this time, which during the period of these experiments corresponded approximately to the date of the April plowing, little was gained by plowing, and that moisture content was nearly equal in the plots plowed in March and April; hence, the yields are nearly equal. After this time the drain on soil moisture from plant growth becomes heavy

enough, unless checked by tillage, to reduce the total moisture in the soil, and consequently the yields from the plots plowed in June are lower.

RESULTS AT NEPHI

Date-of-plowing experiments were conducted at Nephi during the 14-year period 1916 to 1929, inclusive. In 1916 a green-manure test was started at the Nephi station, with wheat as one of the crops to be plowed under at various stages of growth. The volunteer crop on the wheat plots was supplemented with a thin sowing of seed. This test has been used to interpret green-manure relationships as well as to determine the effect of delayed plowing. The assumption that such a test can be used for this twofold purpose probably is somewhat faulty, because seldom if ever does stubble land have a uniform vegetative growth of wheat and weeds. Unquestionably, yields from later plowings, as given in Table 13, are somewhat lower than those from similar plowing on ordinary fallow. From observation of returns on surrounding farms, however, a fairly close relationship has been found to exist between this test and time of plowing on ordinary stubble land.

The time that spring plowing can be started on the dry farms in the Great Basin generally is more or less indefinite because of the variability of the seasons. In some years plowing can be started as early as April 1, in other years not until May 1, and occasionally not until May 15. Because of this fact the different growth stages as given in Table 13 probably are a better guide than is a definite date. For fall plowing the land was turned about October 10. In the spring the first plowing was done as soon as the plow would scour, the second when the wheat growth was 6 inches high (between May 1 and 15), the third when the wheat was 12 inches high (between May 15 and June 1), the fourth when the wheat was just in head (between June 1 and 15), and the fifth when the wheat kernel was in the milk stage, a date which may be as early as June 15 and as late as July 1. The depth of plowing was usually 8 inches.

The experiments were conducted on duplicate tenth-acre plots 36 by 121 feet. The results are shown in Table 13 and graphically in Figures 14 and 15.

TABLE 13.—*Annual and average yields of winter wheat, after fall plowing and after spring plowing at different times, represented by different stages in the growth of wheat at Nephi, Utah, 1916–1929*

Time of plowing	Acre yield (bushels)														
	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
Fall plowing:															
About October 10	20.0	23.6	17.4	21.9	25.5	38.9	14.1	21.6	17.6	29.7	44.0	15.2	20.9	18.3	23.5
Spring plowing:															
Early	17.1	28.8	16.3	22.1	26.2	34.7	12.5	23.8	22.6	32.0	37.0	16.8	29.1	22.3	24.4
When wheat was 6 inches high	16.1	21.9	15.6	16.5	22.2	32.9	10.4	19.6	16.8	25.3	41.6	12.5	21.1	11.7	20.3
When wheat was 12 inches high	15.6	22.6	15.7	17.6	19.0	30.4	9.7	19.0	12.1	23.5	30.0	12.2	14.4	8.1	17.9
When plants were in early bloom	12.6	21.0	10.1	12.9	18.1	26.8	4.3	19.1	5.0	21.7	25.6	9.8	8.4	8.1	14.5
When kernels were in the milk stage	9.9	21.7	9.7	5.5	18.1	27.7	5.3	14.7	3.0	22.3	24.2	7.5	5.1	9.0	13.1

The results shown in Table 13 indicate a very decided advantage in favor of early spring plowing as compared with plowing at later

dates. The yield decreases regularly with the later plowing. The difference between fall plowing and spring plowing in this test was slightly in favor of early spring plowing.

A large part of the plowing on the dry lands in the Great Basin is left until spring. Spring plowing in this section usually is cheaper than fall plowing because less power is needed for the operation and because spring-plowed land does not require so much summer cultivation to check the growth of weeds and volunteer wheat.

These two factors should be considered, but economy of production is of first importance. Usually the time between the first possible opportunity for spring plowing and the time the volunteer wheat is 6 inches high is not more than two weeks; sometimes less. With a large acreage left for spring plowing, a good part of the land can not be plowed before the volunteer wheat is 6 inches high, and it is not uncommon to see plowing done in summer when the wheat plants are in the milk stage, the last stage covered by the experiment. That it pays to work the land as early as possible in the spring is clearly indicated from the results shown in Table 13.

In another experiment, reported later, to determine the influence on yield of different methods of handling summer fallow, a direct comparison also was obtained between the yields of winter wheat on ground plowed for fallow in the spring and in the fall. Yields are available for spring-plowed and fall-plowed fallow given ordinary cultivation during the period 1910 to 1927, inclusive, and for spring-plowed and fall-plowed fallow given no cultivation and weeds hoed during the period 1916 to 1929, inclusive. These data, together with the data for the fall plowing and spring plowing in the experiment presented in Table 13, are shown in Table 14.

TABLE 14.—*Annual and average yields of winter wheat grown on tenth-acre plots plowed in the fall and in the spring with fallow treated in various ways at Nephi, Utah, 1916–1929*

Treatment	Acre yield (bushels)														
	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
Spring plowing; ordinary cultivation	18.3	31.8	14.5	23.7	27.5	38.4	12.8	24.5	21.7	30.4	42.0	17.0	28.8	20.0	25.1
Fall plowing; ordinary cultivation	19.3	27.8	16.2	19.3	27.1	48.0	15.7	23.0	23.8	30.2	52.7	18.5	26.8	16.8	26.1
Spring plowed; weeds hoed	19.5	29.2	13.0	23.0	27.7	42.2	12.2	25.8	21.3	26.8	41.7	18.7	30.5	20.0	25.1
Fall plowed; weeds hoed	17.8	31.2	13.2	21.7	23.8	45.7	12.5	23.3	22.0	29.0	40.0	17.8	24.5	16.7	24.2
Plowed in fall about October 10; ordinary cultivation	20.0	23.6	17.4	21.9	25.5	38.9	14.1	21.0	17.6	29.7	44.0	15.2	20.9	18.3	23.4
Plowed in early spring; ordinary cultivation	17.1	28.8	16.3	22.1	26.2	34.7	12.5	23.8	22.6	32.0	37.0	16.8	29.1	22.3	24.4

As shown in Table 14, the average yield from the two fall-plowed plots is identical with that from the two spring-plowed plots where the treatment of the fallow is normal. When spring plowing with ordinary tillage is compared with spring plowing with no tillage of fallow, the yields are seen to be identical. Making the same comparison between the fall-plowed plots, the difference of 1.9 bushels is in favor of ordinary tillage instead of no tillage with weeds hoed. This experiment conducted over a period of 14 years shows very significantly that the main reason for tillage is weed control.

Using these results as a basis of judgment, it might be stated that dry farmers in the Great Basin who have large areas should plow part of their land to be summer fallowed in the fall, leaving only such an acreage as can be plowed within the first few weeks of spring. On smaller units or on farms so equipped that all of the plowing can be finished within a period not to exceed three weeks, spring plowing is preferable because of lower costs.

DEPTH OF PLOWING EXPERIMENTS

Experiments to determine what effect depth of plowing may have on the yields of wheat grown after summer fallow were conducted at Moro, Lind, and Nephi. At Moro spring and winter wheat was grown on land plowed early in April, both 5 and 10 inches deep. At Nephi winter wheat was grown on land plowed 5 and 10 inches deep in the fall, subsoiled 15 to 18 inches deep, plowed 8 inches deep in the fall and 3 inches deep in the spring, plowed 3 inches deep in the fall and 8 inches in the spring, and plowed 8 inches deep in both fall and spring. At Lind wheat was grown on land plowed 4 and 6 inches deep on two dates—September 1 and November 1—and on land plowed 4, 6, and 8 inches deep on three dates—March 1, April 1, and June 1—until 1926, after which only two depths, 4 and 8 inches, were used.

RESULTS AT MORO

In the depth-of-plowing experiments at Moro 40 tenth-acre plots were used, 20 being in crop and 20 in fallow each year. Plots 3 and 8 in each series of 10 are check plots uniformly cultivated, all being plowed 8 to 9 inches deep and the fallow kept clean. Table 15 shows the yields of each plot in these experiments in the years 1912 and 1914 to 1929, inclusive, no results being available for the year 1913.

TABLE 15.—*Annual and average yields of wheat in the depth-of-plowing experiments at Moro, Oreg., 1912 and 1914–1929*

[Pacific Bluestem spring wheat was grown in 1912 and 1914–1917, Baart spring wheat in 1918 and 1919, and Turkey winter wheat in 1920–1929]

Year	Acre yield (bushels)				Year	Acre yield (bushels)			
	Shallow (5-inch) plowing	Deep (10-inch) plowing	Checks, shallow series	Checks, deep series		Shallow (5-inch) plowing	Deep (10-inch) plowing	Checks, shallow series	Checks, deep series
1912	14.9	15.2	13.2	15.3	1923	28.9	28.9	29.5	29.2
1914	15.0	13.3	14.8	14.3	1924	14.4	14.2	14.7	12.7
1915	15.6	16.8	17.1	15.6	1925	23.8	23.2	25.9	24.8
1916	29.4	31.1	30.3	32.3	1926	21.5	21.2	26.4	21.1
1917	15.9	19.1	16.5	18.2	1927	32.7	33.4	37.3	35.4
1918	13.3	13.4	14.2	12.3	1928	31.3	32.7	36.2	32.5
1919	22.0	21.1	23.6	22.4	1929	9.8	11.9	8.2	9.5
1920	22.0	24.6	24.6	25.3					
1921	35.8	37.4	39.9	39.8	Average	21.4	22.1	23.0	22.2
1922	17.5	18.4	18.2	16.9					

Table 15 shows considerable variation in the average yield of the individual check plots in each series. The check plots (No. 3) located in the west end of each series gave lower average yields than those (No. 8) located in the east end of each series. The average yield of the two check plots in the shallow-plowed series was 23.0 bushels,

and the average yield of the two in the deep-plowed series was 22.2 bushels per acre, indicating that the productivity of the soil of the two series was practically the same. Therefore, the average yields of the eight plots plowed shallow and of the eight plowed deep are safe bases for comparison.

The 17-year average yield of the eight tenth-acre plots plowed 5 inches deep (Table 15) was 21.4 bushels per acre, and the average yield of the eight plots plowed 10 inches deep in the same period was 22.1 bushels per acre, an increase of 0.7 of a bushel in favor of the deep plowing.

RESULTS AT LIND

The depth-of-plowing experiments at Lind included variations in depth on all dates of fall and spring plowing. Fall plowing of fallow is not generally practiced in the Columbia Basin, and therefore only two depths were used on the fall dates. Because fall plowing of fallow is not generally done and also because it has proved to be poor practice, the depth factor for fall plowing was discontinued after 1923. Three depths of plowing were used on each of the spring dates. The results are presented in Table 16.

TABLE 16.—*Annual and average yields of wheat in the depth-of-plowing experiments at Lind, Wash., 1918–1930*

Time and depth of plowing	Acre yield (bushels)													
	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
September 1 (dry):														
Depth 4 inches	3.8	9.3	7.2	9.7	4.6	18.0								
Depth 6 inches	4.0	8.5	7.0	8.0	4.5	18.7								
November 1 (wet):														
Depth 4 inches	4.2	10.5	7.9	11.7	5.0	19.8								
Depth 6 inches	4.0	8.7	7.5	13.7	5.3	20.8								
March (early spring):														
Depth 4 inches	5.2	10.7	7.8	14.0	5.2	21.8	10.0	15.7	16.8	24.7	25.3	9.2	5.5	13.2
Depth 6 inches	5.5	11.7	8.0	12.3	5.6	24.2	9.8	17.7	18.0					
Depth 8 inches	6.2	12.7	7.9	12.3	5.3	23.7	9.0	17.7	18.0	23.8	26.0	7.2	2.5	13.3
April (late spring):														
Depth 4 inches	6.0	11.7	8.1	12.0	4.9	17.7	11.3	15.8	14.0	25.0	25.2	9.0	4.3	12.7
Depth 6 inches	5.7	11.3	6.8	12.5	5.4	18.8	10.5	16.0	14.2					
Depth 8 inches	6.1	11.7	7.7	11.7	5.2	23.2	9.7	17.0	14.7	25.5	25.3	10.0	2.3	13.1
June (early summer):														
Depth 4 inches	5.8	10.0	6.2	11.0	4.5	21.5	2.8	14.5	7.3	24.2	20.2	7.5	5.2	10.8
Depth 6 inches	5.9	11.0	6.4	10.3	5.0	22.8	3.3	14.0	7.8					
Depth 8 inches	6.3	9.3	6.2	10.3	5.0	20.2	3.2	15.7	8.8	23.8	19.8	6.7	4.8	10.8

Dry fall disking lowers the yield (Table 6), presumably because it retards the absorption of soil moisture. The data in Table 16 indicate that with the limited moisture supply and the soil type prevailing at Lind, fall plowing must have had a similar effect. The yields from fall-disked plots (Table 6) are distinctly higher than those from fall-plowed plots (Table 16), which indicates that the detrimental effect must be greater as the depth of the layer of loose soil is increased. It is logical to assume, therefore, that any tillage given while the soil is in a dry condition should be as shallow as possible.

The three spring and summer dates represent plowing under three different conditions of soil moisture and subsequent precipitation. The first represents plowing in a very moist soil with more or less

subsequent rainfall; the second, plowing in a somewhat drier surface soil with less succeeding rainfall; the third, plowing in dry soil with practically no subsequent rainfall.

On the early plowing the average yield from the 4-inch and 8-inch plowing was identical. On the second date of spring plowing the advantage shifted in different years; but because of the greater advantage of some favorable years, it averaged slightly in favor of deep plowing. On the later dates no consistent advantage was shown by the deeper plowing, thus indicating that under drier conditions nothing is gained by increasing the average depth of plowing

RESULTS AT NEPHI

The depth-of-plowing experiment at Nephi is divided into two parts. The purpose of the first section is to determine the effect on the yield of winter wheat of fall plowing to depths of 5, 8, and 10 inches and subsoiling to depths of 15 and 18 inches. In subsoiling, a furrow was first made with a plow and the plow immediately followed by a subsoiler. Ten tenth-acre plots were used each year for these experiments, five being fallow and five producing a crop.

Before the development of the present efficient weeders, fall-plowed land often had to be plowed again in the spring to kill weeds and volunteer growth. The second section of the depth-of-plowing experiment was started in 1916 for the purpose of determining the proper depth of each, if both plowings were necessary. One plot was plowed 8 inches deep in the fall and 3 inches deep in the following spring; another was plowed 3 inches deep in the fall and 8 inches in the spring; and the third was plowed 8 inches deep in both fall and spring. Six tenth-acre plots were used in this test, three of which were fallowed each year and three cropped. The results of both experiments are included in Table 17 and part are shown graphically in Figure 20.

TABLE 17.—*Annual and average yields of winter wheat grown on tenth-acre plots in a depth-of-plowing experiment at Nephi, Utah, 1916–1929*

Treatment	Acre yield (bushels)														
	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
Subsoiled 18 inches deep in fall	16.2	27.7	16.5	19.0	26.8	44.2	15.2	22.5	22.2	30.8	52.7	17.7	25.7	14.2	25.1
Subsoiled 15 inches deep in fall	15.8	27.2	20.3	23.6	24.5	43.4	17.2	21.5	20.8	31.0	49.2	15.7	26.8	12.2	24.9
Plowed 10 inches deep in fall	15.7	28.2	17.3	25.5	24.5	48.2	14.2	25.5	23.5	29.2	51.3	20.2	26.3	17.3	26.2
Plowed 8 inches deep in fall	19.3	27.8	16.2	19.3	27.1	48.0	15.7	23.0	23.8	30.2	52.7	18.5	26.8	16.8	26.1
Plowed 5 inches deep in fall	13.3	28.5	13.7	23.8	22.5	42.7	12.7	20.0	19.2	23.0	45.2	17.3	25.2	16.0	23.1
Plowed 8 inches deep in fall and 3 inches deep in spring	16.5	26.2	18.2	17.3	32.0	41.1	14.8	20.3	21.2	26.9	50.0	16.2	27.3	12.7	24.3
Plowed 3 inches deep in fall and 8 inches deep in spring	14.5	28.2	14.3	15.5	28.0	38.7	13.3	17.8	18.8	24.3	48.7	16.3	24.2	15.5	22.7
Plowed 8 inches deep both in fall and in spring	15.7	26.8	15.8	17.7	27.5	38.4	12.5	19.0	16.5	24.9	40.7	14.7	27.8	14.5	22.3

From the results in Table 17 it is evident that plowing beyond a depth of 8 inches is not necessary. In fact, when the labor costs of subsoiling are considered, this practice is decidedly unprofitable under conditions similar to those at Nephi. Between the 5-inch and 8-inch plowings there was an average difference of 3 bushels in favor of the greater depth for the period from 1916 to 1929. The 8-inch plowing is about identical with the 10-inch plowing. This indicates that fall

plowing should be deeper than 5 inches and need not be deeper than 8 inches. Aside from extra cost, subsoiling actually slightly depressed the yield as compared to 8-inch and 10-inch plowing.

In the second part of Table 17 the 8-inch fall plowing followed by plowing 3 inches deep the following spring gave a higher acre yield than either of the two other methods. Taking all of the data presented in Table 17 into consideration, as well as other data given in this bulletin, it can be safely stated that one plowing either in fall or spring is sufficient if weeds can be controlled.

FIGURE 20.—Annual and average acre yields, in bushels, of winter and spring wheats in varying numbers of years at Moro, Oreg., of spring wheat at Lind, Wash., and of winter wheat at Nephi, Utah, when grown after summer fallow for which the land had been plowed deep (10 inches) and shallow (5 inches)

SUBSTITUTES FOR PLOWING

Plowing has been considered essential as the primary tillage in the preparation of fallow, but under extreme dry-land conditions other methods have been substituted for plowing. Sometimes the substitute method has been considered advantageous because it has left the vegetative residues mixed with the surface soil and aided in the control of soil drifting, and sometimes the substitute method has appeared economical because larger areas can be given the first cultivation with a given power unit in a given time.

At Moro and at Lind fallow prepared by the double-disk harrow was compared with that prepared by plowing. At Lind an unmulched plot on which the weeds were hoed off by hand was added in 1921, and fallow prepared by the duckfoot cultivator also was added to the experiments in 1927. The duckfoot cultivator and double-disk harrow when used as substitutes for plowing do not bury the surface weed seed so completely as does the plow, and frequently the areas where they are used require additional weeding during the fallow season.

The data in Table 18 indicate that plowing is a slightly better method of preparing fallow at Lind than any of the substitutes tried. At Moro disking for fallow gave lower yields of spring wheat than did plowing, but higher yields of winter wheat were obtained, as is also shown in Table 18.

TABLE 18.—*Annual and average yields of wheat in a comparison of plowed fallow with other methods of fallow preparation at Lind, Wash., and Moro, Oreg., 1921–1930*

Treatment	Acre yield (bushels)												
											Average		
	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	10 years (1921–1930)	5 years (1926–1930)	4 years (1927–1930)
RESULTS AT LIND													
Winter and spring wheats:													
Uncultivated (weeds hoed)	11.7	5.0	17.8	11.8	15.5	14.3	20.2	21.5	5.0	3.9	12.7	-------	12.6
Disked (double-disk harrow)	11.3	5.7	20.3	11.4	15.1	14.9	25.3	22.7	9.1	4.4	14.0	-------	15.4
Plowed [1]	13.4	5.8	25.7	9.8	17.7	18.0	25.8	25.7	11.2	5.2	15.8	-------	17.0
Duckfooted	------	------	------	------	------	------	24.8	27.0	8.6	5.6	-------	-------	16.5
RESULTS AT MORO													
Winter wheat:													
Disked fallow	------	------	------	------	------	14.0	22.9	30.7	9.3	20.8	-------	19.5	-------
Plowed fallow	------	------	------	------	------	15.8	23.5	25.2	9.1	19.7	-------	18.7	-------
Spring wheat:													
Disked fallow	------	------	------	------	------	15.3	19.6	23.4	14.8	17.5	-------	18.1	-------
Plowed fallow	------	------	------	------	------	16.4	25.0	20.9	16.3	19.0	-------	19.5	-------

[1] Average of 12 plots for 1921 to 1923 and thereafter single plots.

CULTIVATION OF SUMMER FALLOW

PACKING AFTER PLOWING

The use of surface and subsurface packers has been rather widely advocated, with the idea that it aids in conserving moisture and in increasing wheat yields. At present these implements are used only to a limited extent by dry farmers in the West.

Experiments to determine the effect of packing the soil on the yield of wheat grown after fallow have been conducted at Moro, Oreg., and at Lind, Wash. At Moro both the subsurface and the surface packer were used (Table 10) on land plowed April 1, May 1, and June 1 on which Turkey winter wheat was grown and on early, deep, and shallow spring plowing on which spring wheat was grown. At

Lind the subsurface packer was used on ground plowed in March, April, and June.

RESULTS AT MORO

Table 19 shows the average yields of winter and spring wheat during the 17-year period 1913 to 1929, inclusive, grown on summer-fallowed land not packed and packed with subsurface and surface packers. Both types of packers were used on five different methods of spring plowing, namely, land plowed early and late in the spring and in early summer and plowed shallow and deep in the spring. The subsurface packer also was used on two types of fallow treatments—clean fallow, or fallow frequently cultivated during the summer, and fallow that was harrowed once and given no further cultivation.

TABLE 19.—*Average yields of winter wheat grown at Moro, Oreg., after summer fallow plowed on three different dates and packed with surface and subsurface packers during the 17-year period 1913–1929, and of spring and winter wheat on shallow and deep plowing, clean fallowed and harrowed only once annually during the 18-year period 1912–1929, with 1913 omitted*

Time and depth of plowing and cultivation of fallow	Acre yield (bushels)		
	Not packed	Subsurface packed	Surface packed
DATE OF PLOWING			
April 1 (early spring):			
Clean fallow	30.5	30.6	29.1
One harrowing	26.7	[1] 27.2	
May 1 (late spring):			
Clean fallow	27.5	28.1	26.0
One harrowing	25.4	[1] 25.3	
June 1 (early summer):			
Clean fallow	21.4	21.4	21.2
One harrowing	21.6	[1] 22.0	
Average	[2] 26.5	[2] 26.7	25.4
DEPTH OF PLOWING			
Shallow:			
Clean fallow	21.3	22.9	21.3
One harrowing	19.9	[3] 21.4	
Deep:			
Clean fallow	21.7	24.9	21.9
One harrowing	21.0	[3] 22.0	
Average	[2] 21.5	[2] 23.9	21.6

[1] 15-year average, 1913–1927.
[2] Averages only on clean fallow.
[3] 15-year average, 1912–1927, with 1913 omitted.

The average yields reported in Table 19 are from single tenth-acre plots each year. The yields of winter wheat from the April 1 plowing with clean fallow and the yields of spring wheat from the deep plowing with clean fallow are from adjacent plots. The other yields reported in Table 19 are from plots not adjacent. The detailed results are found in Table 10 and some of the data are shown graphically in Figure 21.

It will be noted from Table 19 that the average yield of Turkey winter wheat on the different dates of plowing and the methods of cultivating the summer fallow were nearly identical for the plots not packed and those packed with the surface packer. There was a slight increase in yield from the subsurface-packed plots when compared

with those not packed or those packed with the surface packer, but the increase was too slight in each case to be significant if the check-plot yields as reported in Table 10 are taken into consideration.

In the depth-of-plowing experiments in which spring wheat was used for 7 years and winter wheat for 12 years, the average yield of

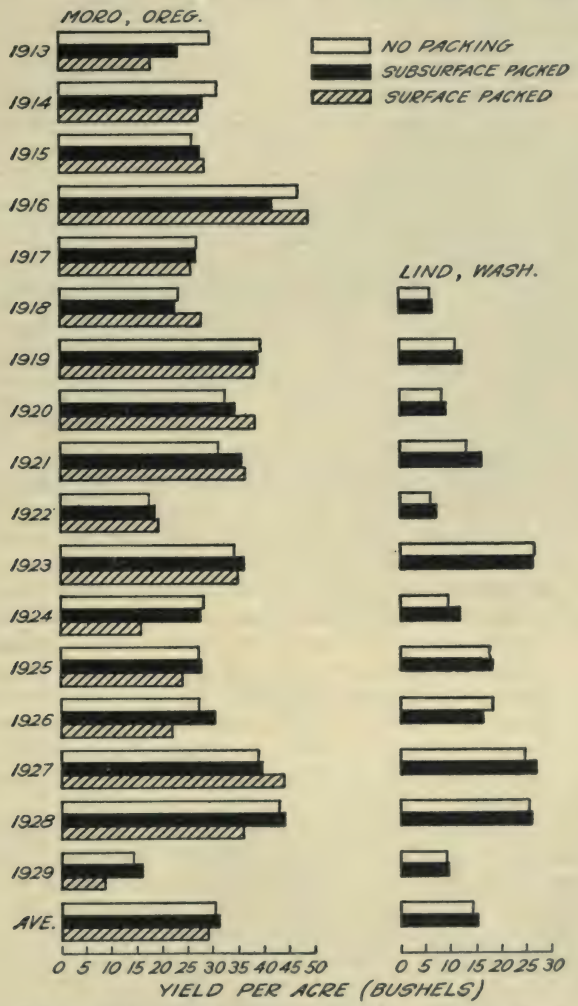


FIGURE 21.—Annual and average acre yields, in bushels, of winter wheat in varying numbers of years at Moro, Oreg., and Lind, Wash., when grown after summer fallow for which the land had been plowed in early spring and either not packed or packed with a subsurface or surface packer after plowing

the subsurface-packed plots was 2.4 bushels more than the average yield of those not packed, but in this case again the increase in yield from the packed ground does not appear to be significant when considered in connection with the differences in yields of the check plots used in this experiment, as reported in Table 15.

RESULTS AT LIND

At Lind the experiments included the use of the subsurface packer on all dates of spring and summer plowing. All the plots of these experiments were disked in early spring, and one-half of those plowed at the summer date were given a second disking in April. The yields for the first two dates are from single plots. The results are given in Table 20.

TABLE 20.—*Annual and average yields of wheat after fallow, packed and not packed, on land plowed on three different dates in the period 1918–1930 at Lind, Wash.*

Time of plowing and subsequent treatment	Acre yield (bushels)													
	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
March (early spring):														
Packed	6.3	12.7	9.1	16.2	6.1	27.0	12.0	17.8	16.3	26.7	25.7	9.5	5.3	14.7
Not packed	6.1	11.2	8.7	13.3	5.1	27.2	9.8	17.7	18.0	24.7	25.5	9.2	5.5	14.0
April (late spring):														
Packed	6.3	14.2	9.0	15.2	6.0	27.8	11.5	14.5	17.3	...	...	...	...	[1] 13.5
Not packed	5.9	12.0	8.1	15.0	5.6	25.7	11.1	16.5	14.7	...	...	...	...	[1] 12.7
June (early summer):														
Packed	5.7	12.3	8.5	12.7	5.1	24.1	7.6	15.0	12.6	26.0	21.2	8.8	3.7	12.6
Not packed	5.8	13.8	8.6	12.8	5.3	24.5	6.2	15.2	13.2	23.2	25.0	10.5	4.3	13.0

[1] 9-year average.

The data in Table 20 indicate that there was a slight benefit in using the packer on the two dates of spring plowing. These data do not contradict those from the other stations but merely emphasize the fact that differences in soil type, soil-moisture content, and subsequent precipitation may cause different results from the same operation. A heavier soil, with heavier rainfall, when given any subsequent tillage whatever, tends to settle into a condition more nearly resembling that produced by the packer than does the lighter soil at Lind under the lighter rainfall. As a result the packer may have little effect in a heavier soil, whereas it had some beneficial effects in the moist soil of the early plowings at Lind. When the soil was dry or nearly dry, as in the June plowing, the packer had no effect on the results.

Despite the possible benefits from using the packer shown by these data, its practical use is doubtful. Weeds grow more rapidly and require more work for their control on packed soil. Especially on light-soil types, where the packer is most beneficial, this additional stirring is likely to cause soil drifting by the wind. That the packer has not come into more general use would tend to cast doubt on its feasibility.

HARROWING AND WEEDING SUMMER FALLOW

Experiments to determine the value of frequency of cultivation of summer fallow after plowing were conducted at Moro, Lind, and Nephi. At Moro three methods were tried: (1) No cultivation of the summer fallow after plowing; (2) one harrowing immediately after plowing and no cultivation thereafter; and (3) two harrowings

immediately after plowing, with sufficient cultivation with a spike-tooth harrow or a rod weeder during the summer to keep the ground free from weeds. At Lind two methods of handling fallow were tried: (1) Immediate cultivation after plowing and (2) delayed

FIGURE 22.—Condition of early spring-plowed ground at Lind, Wash., in 1927 before any cultivation had been done

cultivation, in either case the fallow being kept clean of weeds. At Nephi, no cultivation, moderate cultivation, and frequent cultivation of the fallow also were tested. At all three stations each method

FIGURE 23.—View of a portion of the tillage experimental plots at Moro, Oreg., in 1926. At left, plot given frequent cultivation; at right, plot given no cultivation after plowing

of cultivating the fallow was used on different dates or methods of plowing. Fallow plots or fields at Moro, Lind, and Nephi are shown in Figures 22 to 25, inclusive.

FIGURE 24.—Weeds on fallow ground at Nephi, Utah. Permitting weeds to grow on the fallow reduces wheat yields and makes seed-bed preparation expensive

FIGURE 25.—Clean and well-prepared fallow ground at Nephi, Utah

RESULTS AT MORO

At the Moro station the three methods of cultivating fallow were tried on three dates of spring and summer plowing, namely, April 1, May 1, and June 1. Two methods were tried on four kinds of fall plowing, namely, early and late with the disk and early and late with the moldboard plow.

TABLE 21.—*Average yields of winter and spring wheat at Moro, Oreg., grown after fallow under three methods of cultivation, 1913–1929*

[Spring wheat in 1912 and 1914–1919, and winter wheat 1920–1929]

Crop and time of plowing	Acre yield (bushels)		
	No cultivation	One harrowing	Frequent cultivation
WINTER WHEAT			
Spring plowing:			
Apr. 1	25.7	26.7	30.5
May 1	24.8	25.4	27.4
Summer plowing:			
June 1	21.5	21.6	21.4
Fall plowing:			
Early		23.8	28.1
Late		25.2	25.3
SPRING AND WINTER WHEAT			
Spring plowing:			
Shallow	20.5	19.9	21.3
Deep	20.1	21.0	21.7

The results obtained, as summarized in Table 21, are in favor of frequent cultivation of the summer fallow for winter wheat except on the June plowing. In this instance the ground was dry when plowed, and cultivation of any kind apparently was of no value. On early spring-plowed fallow at Moro cultivation increased winter-wheat yields, but only slightly increased the yields of spring wheat.

The yields shown in Table 21 under the column headed "Frequent cultivation" were obtained from fallow harrowed twice immediately after plowing, harrowed again about three weeks later or when weeds had started, and weeded with a rod weeder two or three times during the summer. On the land plowed in the fall and on that plowed on April 1 Russian thistles were troublesome on the plots given no cultivation and those harrowed only once after plowing. The weeds were allowed to grow on these plots until they attained considerable size, but they were hoed off each year before maturing seed. This weed growth undoubtedly was one cause of the reduced yields on these plots. On the land plowed on May 1 there usually were very few weeds on the fallow and not enough in any year to be a factor reducing wheat yields. On land plowed on June 1 no weeds were able to grow on account of the dry soil.

Table 22 contains a summary of all the results obtained in the tillage experiments with winter wheat at Moro.

TABLE 22.—*Summary of yields of Turkey winter wheat obtained in tillage experiments at Moro, Oreg., conducted on spring and fall plowing, 1914–1929*

Time of plowing	Acre yield (bushels) under different methods of cultivating summer fallow [1]										
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	Average [2]
Spring plowing:											
Apr. 1 (early)	29.0	25.9	28.3	26.7	30.5	29.4	27.8	30.5	31.1	29.8	28.8
May 1 (late)	28.6	25.1	28.1	25.7	28.0	27.4	25.9	30.8	28.7	26.5	27.0
Summer plowing:											
June 1 (early)	27.1	22.4	27.2	22.5	22.3	22.3	22.4	28.6	22.1	21.7	22.9
Average	28.2	24.5	27.9	25.0	26.9	26.4	25.4	30.0	27.3	26.0	26.2
Fall plowing:											
Early (dry)			30.4	23.8	28.1	26.8					26.2
Late (wet)			28.1	25.2	25.3	24.4					25.0
Average			29.3	24.5	26.7	25.6					
Average of all plowings			28.4	24.8	26.8	26.1					

[1] The methods of cultivation are shown on p. 24.
[2] Yields of check plots (3 and 8) are not included in this column.

RESULTS AT LIND

Weed growth has such an important bearing on yield in the portion of the Columbia Basin lying in central Washington that tillage of some sort for weed control can not be omitted in maintaining the fallow. However, the light soil pulverizes very easily after plowing, and each cultivation given increases the tendency of the soil to drift; hence, the practice has arisen of giving as little cultivation as possible while still effecting weed control. The results in a comparison of cultivating immediately after plowing and of delaying cultivation from four to six weeks or until weed growth has started are given in Table 23.

TABLE 23.—*Annual and average yields of wheat after fallow, cultivated immediately and not cultivated immediately after plowing, at Lind, Wash., 1918–1930*

Time of plowing and subsequent treatment	Acre yield (bushels)													
	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
March plowing (early spring):														
Immediate cultivation	6.2	12.3	9.8	15.7	6.6	26.2	11.0	17.7	17.0	25.0	29.5	10.0	6.3	14.9
Delayed cultivation	5.8	13.2	8.3	16.7	6.0	25.5	9.8	17.7	18.0	24.7	25.3	9.2	5.5	14.3
April plowing (late spring):														
Immediate cultivation	6.0	14.2	9.2	16.3	5.8	25.5	11.2	13.2	16.8	26.0	25.8	10.3	5.0	14.3
Delayed cultivation	5.6	12.7	9.5	13.7	5.8	25.0	10.5	16.0	14.2	25.0	25.2	9.0	4.3	13.6
June plowing (early summer):														
Immediate cultivation	5.3	11.3	5.0	12.3	3.6	21.3	7.5	14.0	15.5					[1] 10.6
Delayed cultivation	5.6	9.8	6.4	10.3		16.7	3.3	14.0	7.8					[2] 9.2

[1] 9-year average. [2] 8-year average.

The total number of cultivations depended entirely on seasonal conditions, but the data are approximately a comparison of 3 and 2 cultivations after plowing for the early date, of 2 and 1 cultivations after plowing for the second date, and of 1 and no cultivation after the late plowing. Because immediate cultivation after the dry plow-

ing of the late date increased the tendency of the soil to drift, this modification was discontinued after 1926. Occasionally the second date of plowing required fewer cultivations, and in some years an additional cultivation all around was necessary to control weed growth.

The data given in Table 23 indicate that the tillage given immediately after plowing effected a slight increase in yield; but because the average increase in yield was so slight as to question its profitableness and because so much risk of soil drifting is attendant on this additional cultivation, its recommendation would scarcely seem justifiable.

RESULTS AT NEPHI

At Nephi three methods of cultivating the fallow were tried on fall-plowed and on spring-plowed land. In normal cultivation the fall-plowed land was harrowed early in the spring and again in the fall just before seeding. Between these two cultivations usually two weedings were necessary to kill volunteer growth. The spring-plowed land cultivated normally was harrowed after plowing and again before sowing time in the fall. One weeding sometimes was necessary during early summer. Four plots, two in crop each year, were used for this experiment.

In the second method no cultivation was given to the fallow on fall plowing or on spring plowing, but the weeds were kept down by hoeing with the least possible stirring of the surface soil. Four tenth-acre plots likewise were used for this method, two being fallowed while the other two produced the crop.

In the third method six plots were required. Two plots were fall plowed and one of them plowed again in the spring. One plot was left in stubble for spring plowing. From June 1 until September 1 all of the fallow plots in the third method were harrowed every two weeks. The results of this experiment are presented in Table 24.

TABLE 24.—*Annual and average yields of Turkey winter wheat grown on tenth-acre plots plowed in fall and in spring, or both, with the fallow treated in various ways, at Nephi, Utah, 1916–1929*

Treatment	Acre yield (bushels)														
	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average
Ordinary cultivation:															
Fall plowing	19.3	27.8	16.2	19.3	27.1	48.0	15.7	23.0	23.8	30.2	52.7	18.5	26.8	16.8	26.1
Spring plowing	18.3	31.8	14.5	23.7	27.5	38.4	12.8	24.5	21.7	30.4	42.0	17.0	28.8	20.0	25.1
Weeds hoed:															
Fall plowing	17.8	31.2	13.2	21.7	23.8	45.7	12.5	23.3	22.0	29.0	40.0	17.8	24.5	16.7	24.2
Spring plowing	19.5	29.2	13.0	23.0	27.7	42.2	12.2	25.8	21.3	26.8	41.7	18.7	30.5	20.0	25.1
Cultivated frequently:															
Fall plowing	17.3	27.0	13.6	21.0	23.7	42.3	15.1	21.0	21.2	26.7	52.0	17.2	23.5	13.0	23.9
Spring plowing	18.3	26.4	13.5	19.3	28.5	35.9	15.3	20.8	22.7	27.5	48.5	16.7	28.7	17.7	24.3
Plowed in both fall and spring	17.6	28.5	16.7	21.5	28.0	44.3	15.2	22.8	20.5	31.3	55.2	18.5	23.7	11.0	25.3

In comparing the yields of two normally cultivated plots, one of which was plowed in the fall and the other in the spring, with fall-plowed and spring-plowed plots uncultivated, except for a light hoeing necessary to kill weed growth, the difference in yield of the two fall-plowed plots was only 1.9 bushels, the two spring-plowed plots being identical.

In the frequent cultivation of fallow the difference in yield between fall-plowed and spring-plowed plots was 0.4 of a bushel in favor of the former. The double plowing showed an advantage of exactly 1 bushel per acre over spring plowing. From results in somewhat similar tests elsewhere, double plowing does not seem justified unless necessary to control weeds.

Judged by the results of this experiment from 1916 to 1929, inclusive, it is probable that under conditions similar to those at Nephi cultivation other than that required to control weeds does not pay for the extra labor.

TILLAGE FACTORS INFLUENCING YIELDS AND QUALITY OF WINTER WHEAT

It has been generally accepted without question that the chief purpose of the summer-fallow system is to save moisture for use by the crop during the next season. There are other effects of tillage, however, which have a very important bearing on production and should not be overlooked in considering the problem of the fallow.

Indirectly, because of its influence on soil temperature, aeration, moisture location, etc., tillage has a very marked effect in promoting the activities of soil bacteria; and as a result of this activity and the direct effect of soil stirring and moisture additions the chemical make-up of the soil and consequently the availability of plant food are very materially altered by tillage.

Both at Lind and at Moro moisture studies of the summer-fallow tillage experiments were accompanied by soil studies of nitrate nitrogen; and while not entirely conclusive, these studies brought out certain interesting facts. It is not intended to present the data obtained from these studies in this publication, yet this phase of tillage effects is so important that it should at least be briefly considered.

Each year there were differences in yield from different methods of fallow treatment, and the moisture studies show that these yield differences were not entirely attributable to moisture variations. In a season when rainfall is comparatively abundant, the entire soil body to the depth ordinarily reached by plant roots may be filled with moisture, and in such cases variations in yield can not be attributed to differences in moisture supply. The nitrate-nitrogen studies show, however, that early clean tillage in particular promotes the development of nitrate nitrogen in the soil and that after a year of fallow there are much larger supplies of this plant nutrient in those soils receiving early clean tillage than in those plowed at a late date or on which weeds have been allowed to grow. In years of abundant moisture the yields very closely parallel the soil content of nitrate nitrogen, provided this available nitrogen is not removed by leaching during the winter following the year of fallow.

There have been not only differences in yield but also wide variations in the habit and manner of plant growth and in the quality of the wheat produced on the different fallows. On the June-plowed plots not previously cultivated to keep down weeds and the soil of which was low in nitrate-nitrogen content at seeding time the plants were a lighter green in color, tillered less, had fewer and smaller leaves, grew more slowly, and when mature usually had more slender culms than the plants grown on the early plowed plots cultivated at fre-

quent intervals. During the fallow season and at seeding time the soil of these early plowed plots had a greater nitrate-nitrogen content. Representative plants from the April-plowed and from a June-plowed plot are shown in Figure 26.

Total straw growth always has been greater on the plots with higher nitrate content. As a result of this, owing to the fact that the heavier vegetation more quickly depletes soil moisture, there was a tendency in dry seasons for the crop to burn more readily on the early well-tilled plowing, and also a tendency for grain to be lower in bushel weight because of maturity being hastened. The smaller

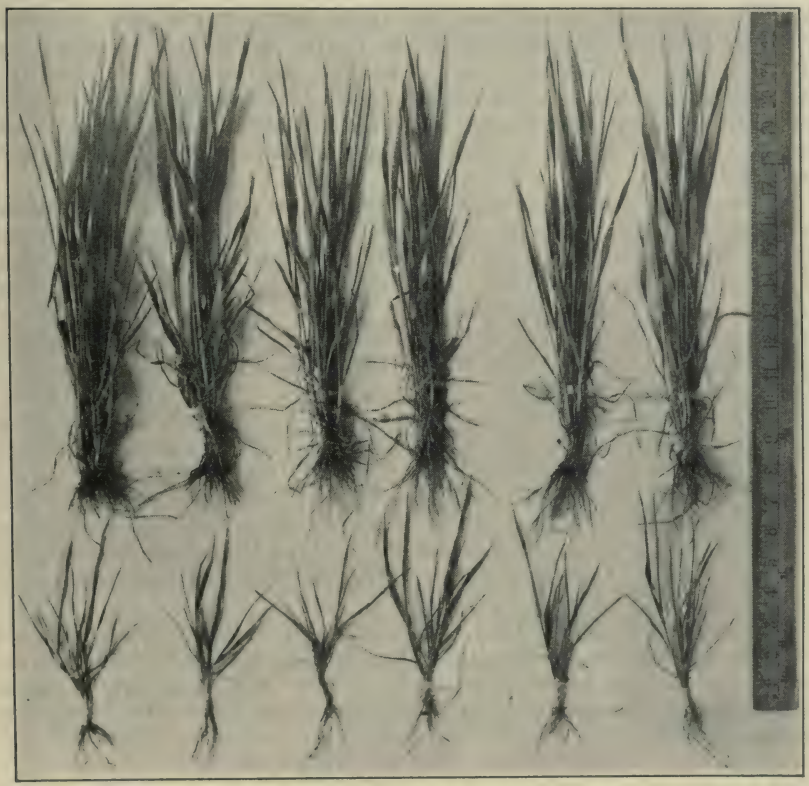


FIGURE 26.—Upper row, representative plants of Turkey winter wheat grown on early plowed and well-cultivated summer fallow at Moro, Oreg. Lower row, same variety sown on same date on late spring-plowed summer fallow. Photographed April 25, 1921

vegetative growth of the crop on the late-plowed or insufficiently cultivated fallow, on the other hand, did not deplete soil moisture so rapidly; the crop ripened more slowly during dry weather, and, as a result, it produced larger, heavier grain.

The quality of the grain produced varied not only in weight but also in composition. That produced on the poor fallow, low in nitrate content, was large and plump with a higher percentage of yellow berry, while that produced on the well-tilled fallow, high in nitrate content, had a tendency to be somewhat lower in bushel weight, and even if of equal weight had a much smaller percentage

of yellow-berry kernels. Analyses showed that the grain from the well-tilled fallow was higher in nitrogen content, and baking tests showed it to be superior in baking quality to that from the poorer fallow.

Considerable moisture is required in the fall to make conditions fit for germination in ground plowed dry or in that from which moisture has been removed by weeds growing on the summer fallow. Ground plowed early in the spring and properly cultivated during the fallow season will require materially less moisture to make a good seed bed. Much heavier seeding is required to secure a good stand of winter wheat on poorly prepared fallow than on that properly handled. Thinner stands on well-tilled early fallow are compensated by greater tillering, owing to the more abundant supply of nitrate nitrogen. On the late-plowed or poorly tilled fallow thin stands generally will tend to reduce yields, because there is not enough available nitrogen to promote tillering. This latter statement, of course, applies only to seasons when moisture is not entirely the limiting factor.

An abundant supply of nitrate nitrogen in the soil at the end of the year of fallow is a very important factor in securing a vigorous growth of winter wheat in the fall, and undoubtedly the plants growing on well-tilled summer fallow are much less liable to winterkill than those on more poorly tilled ground.

Crop yields are the net result of the operation of all soil factors and are limited by one or another of these factors as it may be proportionately less favorable than the others. Under dry farming, moisture usually is the limiting factor, but the degree of its importance in this respect varies considerably. Under extreme conditions moisture alone may determine crop yield; but as rainfall becomes more abundant, it assumes a place second in importance to available plant food. Between these extremes there is every gradation in the relative importance of these two factors, this gradation extending even to individual localities and varying there with seasonal conditions from year to year.

In the drier districts it may be necessary to think only of moisture in tillage operations, leaving the other factors to care for themselves; but as conditions become more favorable and moisture is more abundant, nitrate nitrogen in particular should receive increasing attention.

HARROWING THE GROWING CROP

Experiments to determine what effect the harrowing of winter wheat in the spring has on yield were carried on at Moro, Lind, and Nephi. This is a practice that has been widely followed by farmers in the West, but one concerning the value of which there has been considerable dispute.

RESULTS AT MORO

At Moro there were adjacent plots of winter wheat, one harrowed in the spring and the other not harrowed, on land plowed for summer fallow on several dates and by different methods, as shown in Table

25. This experiment, therefore, was repeated nine times at Moro in each year since 1913. The yields shown in Table 25 are averages for 17 years, 1913 to 1929, for the spring-plowed and summer-plowed plots, and for 16 years, 1914 to 1929, for the fall-plowed plots.

TABLE 25.—*Average yields of Turkey winter wheat from plots harrowed in the spring and not harrowed, at Moro, Oreg., in the 17-year period 1913–1929, for the spring-plowed and the summer-plowed plots and in the 16-year period 1914–1929 for the fall-plowed plots*

Time and method of plowing	Acre yield (bushels)	
	Harrowed	Not harrowed
Plowed April 1 (early spring)	29.1	30.5
Plowed May 1 (late spring)	26.7	27.5
Plowed June 1 (early summer)	21.6	21.4
Plowed early in fall (dry)	26.8	28.1
Plowed late in fall (wet)	24.4	25.3
Average	25.7	26.6

The results shown in Table 25 justify the conclusion that harrowing winter wheat in the spring at Moro decreases yields. The harrowing was done at a time when it was thought it would do the most good and the least damage to the plants. The surface of the soil at Moro gets very hard in the spring and contains numerous shrinkage cracks. Harrowing apparently would put the land in better condition by creating a light mulch and closing the shrinkage cracks, but the yields usually have been slightly decreased by the harrowing. Stands were not appreciably reduced, but harrowing frequently set back the wheat so that it was two or three days later in heading and sometimes a day or two later in ripening than that not harrowed. This delayed maturity probably was caused by covering the wheat plants with small clods turned up by the harrow. Occasionally weeds in the grain can be killed by harrowing, but as a general rule the number of weeds that can be killed by spring harrowing of winter wheat is negligible.

RESULTS AT LIND

At Lind fall conditions were very dry and unfavorable during the first five years of these experiments. The seedlings did not emerge until some time in the winter or early spring, hence all plants were small at the usual time of harrowing winter wheat. Because of these conditions, experiments were outlined with harrowing at varying periods, depending on the size of the plants. The first harrowing was done in the spring immediately after the weather warmed up enough for field work. The second and third harrowings were given at 10-day intervals thereafter. The other treatments were given when the plants were at the stage of growth indicated. The results are presented in Table 26.

TABLE 26.—*Annual and average yields and percentage of loss in stand of Turkey winter wheat in a spring-harrowing experiment at Lind, Wash., 1919–1928, omitting 1925*

Harrowing treatment	Acre yield and loss in stand										Acre yield					
	1919		1920		1921		1922		Average, 1919–1922		1923	1924	1926	1927	1928	Average, 1919–1928
	Yield	Stand loss	Yield	Stand loss	Yield	Stand loss	Yield	Stand loss	Yield	Stand loss						
	Bu.	*P. ct.*	*Bu.*	*P. ct.*	*Bu.*	*P. ct.*	*Bu.*	*P. ct.*	*Bu.*	*P. ct.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*
Unharrowed (check)	13.0	----	9.4	5.1	14.7	24.2	5.8	----	10.7	----	25.7	9.0	12.8	20.5	23.8	15.0
Harrowed once	12.8	23.7	9.5	27.2	14.3	20.2	6.0	2.3	10.7	18.4	23.8	10.2	13.4	21.3	23.0	14.9
Harrowed twice	11.7	51.6	9.7	35.0	13.6	53.0	6.2	8.3	10.3	37.0	22.3	10.8	14.1	20.1	22.2	14.5
Harrowed three times	10.4	62.9	7.7	52.3	14.5	61.2	6.1	31.3	9.7	51.9	25.7	----	----	----	----	----
Harrowed when covering the ground or just before jointing	13.3	40.5	10.2	16.5	14.3	32.7	5.5	24.9	10.8	28.7	26.6	11.0	15.4	20.5	22.5	15.5
Harrowed just before jointing and again when 6 inches high	11.2	----	9.8	8.9	13.5	28.5	5.4	5.5	10.0	14.3	----	----	----	----	----	----

Plant counts were made both before and after cultivation in 1920 and 1921 and after the cultivation was completed in 1919 and 1922, to determine the effect of the cultivation on the stands. The data as presented in Table 26 lead to the conclusion that any cultivation of the crop before it reaches the stage when it is large enough to cover the ground is injurious to the stand, and even under the severe conditions of the period of these experiments, when thinner stands might be presumed to have been at a greater advantage, thinning at the early stages did not increase average yields. The data further suggest that the only cultivation which is not detrimental or which may be of any advantage is that given just before jointing.

RESULTS AT NEPHI

From 1909 to 1915 an experiment was conducted at the Nephi Substation to determine the effect of harrowing growing wheat. In 1923 a similar experiment was started with wheat seeded in spaced rows 7, 14, 21, and 28 inches apart. Yield data for the plots with rows spaced different distances apart are shown in Table 51. The data given in Table 27 are from single tenth-acre plots for 1909 to 1915 and are averages from all widths of sowing for cultivated and uncultivated wheat for the years 1923 to 1929. Each yearly yield for the latter period represents an average of eight twentieth-acre plots.

TABLE 27.—*Annual and average yields of Turkey winter wheat on plots harrowed in the spring and not harrowed at Nephi, Utah, for stated years*

Year	Acre yield (bushels)		Year	Acre yield (bushels)	
	Cultivated	Uncultivated		Cultivated	Uncultivated
1909	8.3	12.7	1924	21.2	22.8
1910	19.0	19.5	1925	29.4	34.3
1911	27.9	27.7	1926	35.6	35.9
1912	14.9	14.9	1927	17.8	18.2
1913	9.8	10.5	1928	33.0	30.9
1914	33.6	28.5	1929	19.5	21.7
1915	25.3	25.0			
1923	20.9	24.6	Average	22.6	23.4

The results presented in Table 27 show that harrowing of the growing crop reduced the average acre yield 0.8 of a bushel.

RATE AND DATE OF SEEDING EXPERIMENTS

The time when wheat is sown and the rate at which it is sown may markedly influence yields. The time and rate of sowing wheat affect the stand obtained, the tillering of the plants, the quantity and length of straw, and the time of ripening. These also may be influenced by other factors, such as viability of the seed, method of seed treatment for bunt, condition of the seed bed, depth of sowing, winterkilling, soil moisture, and plant food in the soil. The reason for a thin stand frequently may be difficult to determine, on account of the number of factors involved. A thin stand of wheat generally is not desirable. It gives weeds a better chance to grow and thereby may seriously reduce yields, or in the absence of weeds a thin stand may not produce enough plants or heads to obtain maximum yields. A stand also may be so thick that there will be insufficient moisture to enable the crop to mature properly.

Rate and date of sowing experiments with both winter and spring wheat were carried on at the three stations, Moro, Lind, and Nephi. At each station the experiment was on fallowed ground, plowed early and kept free from weeds.

RESULTS AT MORO

WINTER WHEAT

Experiments to determine the best rates and dates of sowing for Turkey winter wheat were conducted at Moro, Oreg., during the 12 years from 1916 to 1928, inclusive, omitting 1925. Rate-of-sowing experiments were conducted also in 1914 and 1915. The date of sowing was not the same each year, varying according to the time at which moisture conditions were favorable to begin sowing. The earliest date was September 9 and the latest December 1. Five sowings, at about 2-week intervals, were made in the fall of 1916, 1917, 1921 to 1924, and 1926 to 1928, and four sowings in the fall of 1918, 1919, and 1920.

TABLE 28.—*Annual and average yields of Turkey winter wheat in rate-and-date-of-seeding experiments conducted at Moro, Oreg., 1916–1928, omitting 1925*

Rate of seeding	Average date of seeding	Acre yield (bushels)												
		1916	1917	1918	1919	1920	1921	1922	1923	1924	1926	1927	1928	Average
2 pecks	Sept. 14	33.0	28.3	16.7	31.7	40.0	29.7	25.3	36.9	27.7	27.4	26.7	36.8	30.0
	Sept. 28	48.3	21.0	22.3	33.0	35.0	46.0	26.4	35.7	25.0	28.5	25.7	40.6	32.3
	Oct. 12	49.8	14.0	.....	35.3	24.7	34.3	24.5	37.7	17.7	24.2	30.8	38.7	[1] 30.2
	Oct. 27	23.3	13.3	16.3	27.3	24.3	28.0	21.9	41.0	18.0	20.7	36.5	29.1	25.0
	Nov. 14	21.6	16.0	17.0	.....	.....	23.0	23.7	44.4	13.0	21.8	40.1	27.6	[2] 24.8
Average	.....	35.2	18.5	18.1	31.8	31.0	32.2	24.4	39.1	20.3	24.5	32.0	34.6	28.5
3 pecks	Sept. 14	30.0	34.0	19.0	34.3	43.0	44.3	27.7	37.7	28.3	27.9	29.7	37.6	32.8
	Sept. 28	41.2	23.0	26.6	31.3	39.3	41.7	26.1	35.0	17.3	27.9	25.8	40.3	31.3
	Oct. 12	44.0	13.7	.....	38.3	29.0	37.3	26.1	35.7	15.0	26.6	30.0	41.4	[1] 30.6
	Oct. 27	23.3	13.0	16.6	28.7	25.3	28.7	24.8	41.7	16.3	20.2	37.0	33.7	25.8
	Nov. 14	22.3	17.0	17.3	.....	.....	23.6	24.5	41.5	14.0	20.2	26.7	27.2	[2] 23.4
Average	.....	32.2	20.1	19.9	33.2	34.2	35.1	25.8	38.3	18.2	24.6	29.8	36.0	28.9

[1] 11-year average. [2] 10-year average.

TABLE 28.—*Annual and average yields of Turkey winter wheat in rate-and-date-of-seeding experiments conducted at Moro, Oreg., 1916–1928, omitting 1925*—Con.

Rate of seeding	Average date of seeding	Acre yield (bushels)												
		1916	1917	1918	1919	1920	1921	1922	1923	1924	1926	1927	1928	Average
4 pecks	Sept. 14	23.7	35.3	20.3	34.0	40.7	42.0	28.8	37.2	25.0	27.9	25.7	38.3	31.6
	Sept. 28	40.6	22.7	26.0	26.7	37.7	44.0	27.4	34.0	17.0	27.9	30.3	40.3	31.2
	Oct. 12	35.0	18.3	.....	37.7	26.0	43.7	26.7	37.3	18.0	26.6	32.8	41.4	[1] 31.2
	Oct. 27	33.3	13.7	19.0	33.3	22.0	31.7	23.7	40.0	17.0	21.8	35.7	33.0	27.0
	Nov. 14	25.3	18.0	20.0	.....	.....	25.7	25.1	47.9	16.3	21.5	36.0	28.8	[2] 26.5
Average		31.6	21.6	21.3	32.9	31.6	37.4	26.3	39.3	18.7	25.1	32.1	36.4	29.5
5 pecks	Sept. 14	23.3	38.3	17.3	36.7	49.3	42.3	29.3	34.4	24.7	25.8	27.3	36.4	32.1
	Sept. 28	53.0	25.3	25.6	38.0	39.7	41.7	26.9	30.7	18.5	25.3	29.5	39.5	32.8
	Oct. 12	28.3	20.3	.....	42.0	25.0	39.7	27.5	34.7	18.0	26.9	34.0	39.1	[1] 30.5
	Oct. 27	40.6	13.7	21.0	31.7	21.0	31.3	26.4	40.3	16.0	19.6	36.3	34.9	27.7
	Nov. 14	30.0	18.6	21.6	.....	.....	25.3	24.0	45.3	13.3	20.2	36.3	28.0	[2] 26.3
Average		35.0	23.2	21.4	37.1	33.8	36.1	26.8	37.1	18.1	23.6	32.7	35.6	30.0
6 pecks	Sept. 14	31.3	34.3	22.0	36.0	42.3	37.7	29.6	33.7	23.3	26.3	34.7	35.3	32.2
	Sept. 28	25.6	28.7	25.3	34.5	38.7	44.0	25.3	34.7	24.0	29.6	35.0	38.7	31.8
	Oct. 12	28.0	23.0	.....	40.0	26.3	36.3	29.6	36.3	17.0	25.0	33.3	40.3	[1] 30.5
	Oct. 27	40.0	14.0	27.0	34.7	17.3	27.7	25.1	40.7	15.0	19.1	35.7	33.0	27.4
	Nov. 14	30.6	20.3	19.0	.....	.....	25.7	24.5	44.9	14.3	21.8	35.7	29.5	[2] 26.6
Average		31.1	23.7	23.3	36.3	31.2	34.3	26.8	38.1	18.7	24.4	34.9	35.4	29.8
7 pecks	Sept. 14	38.3	26.3	24.7	36.3	45.3	42.0	33.6	34.4	19.3	25.8	33.0	37.6	33.1
	Sept. 28	21.3	27.0	27.7	39.3	40.8	40.0	26.4	35.3	25.0	26.1	32.8	38.7	31.7
	Oct. 12	30.0	25.3	.....	41.0	27.0	37.0	27.7	30.7	19.5	28.2	30.7	40.6	[1] 30.7
	Oct. 27	41.6	14.5	26.6	32.7	22.3	31.3	25.3	39.3	14.7	18.5	38.0	35.3	28.3
	Nov. 14	26.3	20.6	23.3	.....	.....	25.7	25.3	45.4	15.3	21.2	34.0	28.9	[2] 26.6
Average		31.5	22.7	25.6	37.3	33.9	35.2	27.7	37.0	18.8	24.0	33.7	36.2	30.2
8 pecks	Sept. 14	38.0	21.0	25.7	32.3	49.3	41.3	33.6	34.2	23.7	26.1	34.3	39.5	33.3
	Sept. 28	23.0	24.7	29.7	33.8	37.7	39.7	26.4	34.0	22.5	26.6	28.5	39.1	30.5
	Oct. 12	32.0	26.3	.....	38.3	29.3	39.3	30.4	35.7	22.5	28.8	27.7	42.0	[1] 32.0
	Oct. 27	43.0	14.0	28.7	30.3	25.7	25.0	25.9	39.3	13.0	19.4	36.7	34.9	28.0
	Nov. 14	24.6	22.6	20.3	.....	.....	26.3	23.7	43.9	14.0	22.0	35.7	28.0	[2] 26.1
Average		32.1	21.7	26.1	33.7	35.5	34.3	28.0	37.4	19.1	24.6	32.6	36.7	30.1

SUMMARY OF TOTAL AND AVERAGE YIELDS PER ACRE

Average date of seeding	Yields at all rates of seeding (bushels)	
	Total	Average
Sept. 14	2,699.8	32.1
Sept. 28	2,659.5	31.7
Oct. 12	2,372.9	30.8
Oct. 27	2,271.3	27.0
Nov. 14	1,803.1	25.8

[1] 11-year average. [2] 10-year average.

The quantity of seed sown, shown in Table 28 as pecks per acre, indicates where the drill was set and not the actual pounds of seed sown. Prior to 1924 all the seed was soaked in a standard formaldehyde solution for 5 minutes to kill bunt spores, and was allowed to dry about 24 hours before sowing. From 1924 on, copper carbonate was used for treating wheat for bunt.

Figure 27 presents in graphic form the average yield obtained from all rates on each of the five dates.

Table 28 shows that there were rather wide variations each year in the yields of single plots sown at different rates or on different dates.

The two earliest average dates of seeding, September 14 and September 28, gave the highest average yields, as shown in Tables 28 and 29. The yield obtained from the third date, October 12, was nearly as high, but the yields from the two later dates, October 27 and November 14, were significantly less.

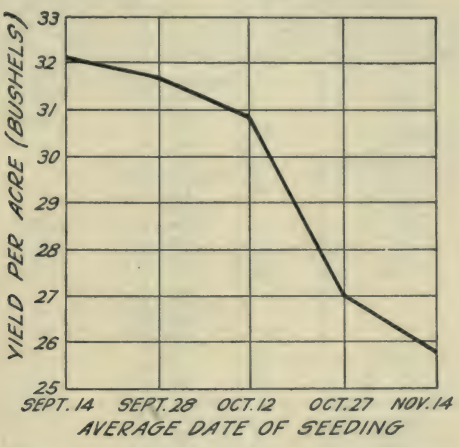


FIGURE 27.—Average acre yields of Turkey winter wheat sown at all rates from 2 to 8 pecks per acre on each of five successive dates, September 14 to November 14, in the 12 years 1916–1924 and 1926–1928, at the Sherman County Branch Station, Moro, Oreg.

TABLE 29.—*Average yields of Turkey winter wheat in the rate-and-date-of-seeding experiments at Moro, Oreg., 1916–1928, omitting 1925*

Rate of seeding	Acre yield (bushels)						
	Average date of seeding					Average	
	Sept. 14	Sept. 28	Oct. 12	Oct. 27	Nov. 14	Actual	Net [1]
2 pecks	30.0	32.3	30.2	25.0	24.8	28.5	28.0
3 pecks	32.8	31.3	30.6	25.8	23.4	28.9	28.2
4 pecks	31.6	31.2	31.2	27.0	26.5	29.5	28.6
5 pecks	32.1	32.8	30.5	27.7	26.3	30.0	28.8
6 pecks	32.2	31.8	30.5	27.4	26.6	29.8	28.3
7 pecks	33.1	31.7	30.7	28.3	26.6	30.2	28.5
8 pecks	33.3	30.5	32.0	28.0	26.1	30.1	28.1
Average	32.2	31.7	30.8	27.0	25.8	29.6	28.4

[1] After deducting seed.

The time of emergence of the winter-wheat plants has not always borne a consistent relation to time of sowing. In some years rains came so late that the wheat sown on the first three dates emerged at about the same time. Late-sown winter wheat usually does not emerge for about a month after seeding, on account of the prevailing cooler weather. Sometimes the plants of the late-sown wheat do not emerge until early spring. The dates of seeding, the dates of emergence, and the number of days from sowing to emergence are shown in Table 30.

TABLE 30.—*Dates of seeding and of emergence and number of days from seeding to emergence of Turkey winter wheat sown on various dates at Moro, Oreg., 1914–1928, omitting 1925*

Date sown	Date of emergence	Time from seeding to emergence (days)	Date sown	Date of emergence	Time from seeding to emergence (days)
Season of 1914:			Season of 1922:		
Sept. 23	Oct. 8	15	Sept. 12	Oct. 10	28
Season of 1915:			Sept. 26	Oct. 18	22
Oct. 21	Nov. 7	17	Oct. 10	Nov. 5	26
Season of 1916:			Oct. 24	Nov. 15	22
Sept. 18	Sept. 25	7	Nov. 8	[1]	
Oct. 2	Oct. 17	15	Season of 1923:		
Oct. 18	Nov. 5	18	Aug. 25	Oct. 13	49
Nov. 3	[1]		Sept. 8	do	35
Nov. 15	[1]		Sept. 22	do	21
Season of 1917:			Oct. 7	Oct. 18	11
Sept. 22	Oct. 12	20	Oct. 20	Nov. 9	20
Oct. 7	Oct. 25	18	Nov. 4	Jan. 2	59
Oct. 21	[1]		Nov. 18	Jan. 20	63
Nov. 6	[1]		Season of 1924:		
Dec. 1	[1]		Sept. 8	Oct. 6	28
Season of 1918:			Sept. 22	Oct. 4	12
Sept. 27	Dec. 17	81	Oct. 5	Oct. 17	12
Oct. 11	do	67	Oct. 20	Nov. 19	30
Nov. 5	do	42	Nov. 2	Nov. 29	27
Nov. 27	[1]		Season of 1926:		
Season of 1919:			Sept. 19	Oct. 21	32
Sept. 9	Sept. 16	7	Oct. 3	Oct. 23	20
Sept. 23	Oct. 2	9	Oct. 17	Oct. 31	14
Oct. 10	Nov. 5	26	Oct. 31	Dec. 12	42
Oct. 25	Nov. 20	26	Nov. 13	Jan. 18	66
Season of 1920:			Season of 1927:		
Sept. 16	Sept. 25	9	Sept. 15	Oct. 25	40
Sept. 30	Oct. 16	16	Sept. 29	Nov. 2	34
Oct. 15	Nov. 22	38	Oct. 13	Oct. 28	15
Oct. 29	[1]		Oct. 27	Nov. 29	33
Season of 1921:			Nov. 10	Jan. 6	57
Sept. 8	Sept. 17	9	Season of 1928:		
Sept. 22	Oct. 1	9	Sept. 14	Sept. 24	10
Oct. 7	Oct. 22	15	Sept. 28	Oct. 8	10
Oct. 12	Dec. 4	53	Oct. 12	Oct. 22	10
Nov. 3	[1]		Oct. 26	Nov. 16	21
			Nov. 10	Dec. 6	26

[1] Did not emerge until spring.

TABLE 31.—*Average yields of Turkey winter wheat in rate-of-seeding experiments at Moro, Oreg., 1914–1928, omitting 1925*

Year [1]	Acre yield from rate of seeding shown						
	2 pecks	3 pecks	4 pecks	5 pecks	6 pecks	7 pecks	8 pecks
	Bush.	*Bush.*	*Bush.*	*Bush.*	*Bush.*	*Bush.*	*Bush.*
1914	12.6	12.6	14.1	13.3	16.4	17.5	17.5
1915	15.4	15.0	18.7	19.5	20.0	20.3	20.8
1916	43.7	38.4	33.1	34.9	28.3	29.9	31.0
1917	21.1	23.6	25.4	28.0	28.0	26.2	24.0
1918	18.4	20.7	21.8	21.3	24.8	26.3	28.0
1919	33.3	34.6	32.8	38.9	36.8	38.9	34.8
1920	33.2	37.1	34.8	38.0	35.8	37.7	38.8
1921	36.7	41.1	43.2	41.2	39.3	39.7	40.1
1922	25.4	26.6	27.6	27.9	28.2	29.2	30.1
1923	36.8	36.1	36.2	33.3	34.9	33.5	34.6
1924	23.5	20.2	20.0	20.4	21.4	21.3	22.9
1926	26.7	27.5	27.5	26.0	27.0	26.7	27.2
1927	27.7	28.5	29.6	30.3	34.3	32.2	30.2
1928	38.7	39.8	40.0	38.3	38.1	39.0	40.2
Total	393.2	401.8	404.8	411.3	413.3	418.4	420.2
Average	28.1	28.7	28.9	29.4	29.5	29.9	30.0
Net yield	27.6	28.0	27.9	28.2	28.0	28.2	28.0

[1] For 1914 and 1915 the yields are averages obtained from duplicate tenth-acre plots. For the balance of the period the yields are averages obtained from twentieth-acre plots for the three earliest dates of sowing each year.

Table 31 shows the yields obtained by sowing Turkey winter wheat at rates varying from 2 to 8 pecks per acre, in the 14 years from 1914 to 1928, inclusive, omitting 1925. Only one date of sowing is included for 1914 and 1915, but the yields for these years are averages obtained from duplicate tenth-acre plots. The yields from each rate are averages of the three twentieth-acre plots used for the three earliest dates of sowing for all other years, as shown in Table 28. The results are summarized graphically in Figure 28.

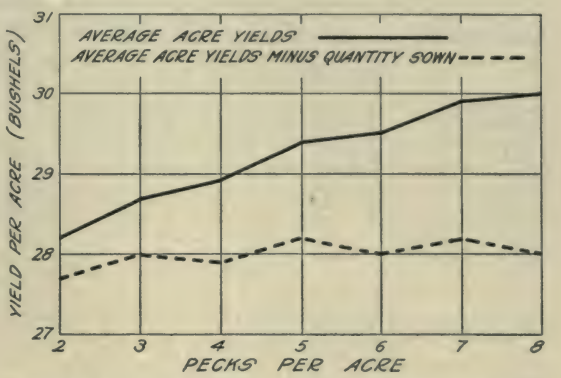


FIGURE 28.—Average actual acre yields and average net acre yields obtained from sowing Turkey winter wheat at different rates, varying from 2 to 8 pecks per acre, in the 14 years 1914–1924 and 1926–1928, at the Sherman County Branch Station, Moro, Oreg. The net yields are the actual yields minus the quantity sown

The average yields obtained from the different rates of sowing are remarkably similar, indicating that on well-cultivated summer-fallowed ground the rate of sowing of winter wheat may not be an important factor in influencing yields. From the standpoint of the farmer, however, there is considerable advantage in sowing the wheat thick enough to insure good stands. A thin stand of wheat allows so much space for weeds to grow that yields may be reduced on that account. Thick sowing, therefore, has the advantage of suppressing weed growth.

SPRING WHEAT

Experiments combining rate and dates of seeding were conducted with Pacific Bluestem wheat at Moro in the nine years from 1912 to 1920, inclusive. This variety was sown early and late in the spring at rates varying from 2 to 8 pecks per acre. After 1918 only the early date was used. In 1919 this variety was sown at rates varying from 4 to 8 pecks and in 1920 at rates from 5 to 8 pecks. The results of this experiment are shown in Table 32.

The highest average yields were obtained from the early sowing. On account of its earlier maturity, early sown spring grain usually outyields late-sown grain in the Columbia Basin district. Comparing the rates of seeding, it will be noted from Table 32 that the highest average net yield was obtained from the 5-peck sowing on the early date and from the 3-peck sowing on the late date. As with the winter wheat the difference in the yields obtained from the varying rates is not great except in the case of late sowing, where the thinner rates consistently give the higher yields.

TABLE 32.—*Annual and average yields per acre of Pacific Bluestem spring wheat at Moro, Oreg., sown early and late in the spring at rates varying from 2 to 8 pecks in part or all of the years 1912–1920*

EARLY SPRING SEEDING [1]

Rate of seeding	Acre yields (bushels)											
	Date of seeding									Total	Average	
	Mar. 25, 1912	Mar. 25, 1913	Mar. 26, 1914	Mar. 22, 1915	Mar. 31, 1916	Apr. 5, 1917	Mar. 19, 1918	Mar. 25, 1919	Apr. 2, 1920		7 years, 1912–1918	9 years, 1912–1920	Net [2]
2 pecks	7.0	18.5	17.5	18.6	23.2	12.1	15.7	.....	.....	112.6	16.1	.....	15.6
3 pecks	8.8	17.5	15.5	18.6	23.3	15.2	15.7	.....	.....	114.6	16.4	.....	15.6
4 pecks	13.6	20.8	14.5	15.1	23.0	15.7	17.3	22.6	.....	142.6	17.1	.....	16.1
5 pecks	12.5	21.3	17.8	17.2	23.0	17.9	18.0	24.8	18.6	171.1	18.2	19.0	[3] 17.7
6 pecks	10.5	18.3	16.3	20.6	19.3	18.1	18.0	22.9	16.7	160.7	17.3	17.9	[3] 16.4
7 pecks	13.1	20.0	17.3	18.0	19.3	17.3	15.3	22.8	19.8	162.9	17.2	18.1	[3] 16.3
8 pecks	13.1	20.0	18.1	19.2	24.0	20.8	15.5	23.6	18.5	172.8	18.7	19.2	[3] 17.2

LATE SPRING SEEDING [4]

Rate of seeding	Apr. 26, 1912	Apr. 25, 1913	Apr. 16, 1914	Apr. 15, 1915	May 1, 1916	Apr. 28, 1917	Apr. 22, 1918						
2 pecks	7.8	10.5	13.7	10.4	18.8	14.7	9.7	.....	.....	85.6	12.2	.....	11.7
3 pecks	15.5	10.0	11.7	10.4	20.5	13.3	9.7	.....	.....	91.1	13.0	.....	12.3
4 pecks	11.8	7.7	8.7	11.1	18.8	13.6	14.3	.....	.....	86.0	12.3	.....	11.3
5 pecks	14.0	7.6	5.3	10.5	22.6	13.3	12.0	.....	.....	85.3	12.2	.....	11.0
6 pecks	15.1	8.3	3.7	11.4	20.2	12.8	12.7	.....	.....	84.2	12.0	.....	10.5
7 pecks	15.5	10.4	4.0	12.8	17.7	12.0	12.0	.....	.....	84.4	12.1	.....	10.4
8 pecks	15.5	13.1	3.7	10.2	19.6	11.8	11.0	.....	.....	84.9	12.1	.....	10.1

[1] Average date, Mar. 27.
[2] After deducting seed.
[3] 9-year net average.
[4] Average date, Apr. 23.

In Table 33 data are given on a rate-of-seeding experiment with early sown Marquis spring wheat for the years 1917 to 1921, inclusive. The results shown in the table are the yields obtained from single twentieth-acre plots each year. The results of the four years indicate a slight advantage from the heaviest rates used, namely, 6 and 7 pecks to the acre.

TABLE 33.—*Annual and average yields of Marquis spring wheat sown at Moro, Oreg., at various rates per acre in the 5-year period from 1917 to 1921, inclusive*

Rate of seeding	Acre yield (bushels)							
	Date of seeding					Total	Average	
	Apr. 5, 1917	Apr. 11, 1918	Mar. 25, 1919	Apr. 2, 1920	Mar. 30, 1921		Actual (Apr. 3)	Net [1]
4 pecks	16.0	14.9	18.7	18.6	20.3	88.5	17.7	16.7
5 pecks	18.7	18.2	18.9	16.5	19.7	92.0	18.4	17.2
6 pecks	17.9	18.6	18.7	20.0	20.3	95.5	19.1	17.6
7 pecks	21.6	18.6	20.0	17.8	18.9	96.9	19.4	17.6

[1] After deducting seed.

RESULTS AT LIND

WINTER WHEAT

Because of the very unfavorable fall conditions that prevailed at Lind, experiments on rates and dates of seeding with winter wheat have been very unsatisfactory. The most that can be learned from the date-of-seeding experiments is the comparative merit of (1) seeding in the dry soil before rains and (2) waiting until after the rains before seeding. Results of experiments on dates of seeding winter wheat are given in Table 34.

TABLE 34.—*Annual stands and yields of Turkey winter wheat sown at the rate of 60 pounds per acre in date-of-seeding experiments at Lind, Wash., 1919–1928, omitting 1925*

Time of seeding	1919		1920		1921		1922		1923	
	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield
		Bu.		Bu.		Bu.		Bu.		Bu.
Early (Sept.)	220,000	15.8	128,000	9.2	527,000	12.2			148,000	16.0
Midseason (Oct.)	380,000	16.9	164,000	9.8	776,000	11.2	366,000	5.7	298,000	24.3
Late (Nov.)	375,000	13.9	180,000	10.5	941,000	11.5	96,000	3.4	516,000	25.7

Time of seeding	1924		1926		1927 [2]		1927		1928	
	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield
		Bu.		Bu.		Bu.		Bu.		Bu.
Early (Sept.)	698,000	12.5				23.5	242,000	27.0		25.8
Midseason (Oct.)					228,000	10.5	233,000	21.3		18.1
Late (Nov.)	116,000	6.5	371,000	14.8						

[1] Plants per acre. [2] This series on northern slope, all others on southern slope.

Conditions varied so greatly from season to season that yearly data can not safely be averaged. In the fall of 1918 dry weather was continuous and conditions were so unfavorable that no seeding of any sort was attempted prior to October 1. Rains came about October 25, and second seedings were put in at this date, the late seedings being made on November 15. In 1919 fall conditions seemed somewhat more favorable, and the earliest seedings were made on September 15, and second and third seedings on October 15 and November 15. The early promise did not materialize, however, and no rains in any quantity came before November 15. As a result of these unfavorable seasonal conditions, emergence of all sowings for both years occurred in midwinter. In the fall of 1920, on the other hand, some rain came comparatively early; and while not of enough volume to promote the best growth and development, the plants from the first seeding date made some growth before the others emerged. These light rains later largely evaporated, so that the later seedings also emerged in midwinter.

In 1921 fall conditions were again very unfavorable. The first rains of any consequence came in the latter part of October when the first sowings were made, but the rains were not sufficient to maintain growth and both sowings emerged in the spring with poor stands of weak plants. In the fall of 1922 both the early and midseason sowings were made in partially dry seed beds, which induced a protracted germination, and the third sowing was the only one favored with rains sufficient to give prompt germination. Cold weather prevented complete emergence of all sowings, however, until midwinter or early spring. In the falls of 1923, 1926, and 1927 both sowings were made in moist seed beds. In all three years the first sowings emerged promptly in the fall. The second sowings in the fall of 1923 emerged during the winter and early spring, and for 1926 and 1927 with favorable moisture conditions they emerged in midwinter.

Remembering that rains sufficient to give a moist seed bed came for the 1919 crop at the time of the second seeding, for the 1920 crop at the time of the late (third) seeding, for the 1921 crop at the time of the early (first) seeding, for the 1922 crop at the time of the October seeding, and for the 1923 crop at the time of the late seeding, the data for the first five years indicate that under very dry conditions nothing is gained by seeding in the dry soil before fall rains. Remembering also that for the crops of 1924, 1927, and 1928 all seedings were made in a moist seed bed, the data indicate that under more favorable conditions early seeding is a decided advantage. The data for 1927 further indicate that late seeding in a favorable season was at a decided disadvantage on northern slopes.

The data covering rate-of-seeding experiments are given in Table 35. These experiments were subject to the same unfavorable conditions as applied to the date of seeding.

TABLE 35.—*Annual and average actual and average net yields of Turkey winter wheat in rate-of-seeding experiments on various dates at Lind, Wash., 1919–1926, omitting 1925*

Time and rate of seeding	Acre yield (bushels)								
	1919	1920	1921	1922	1923	1924	1926	Average	
								Actual	Net [1]
Early fall date:									
2 pecks	.....	7.1	13.0	.....	15.1	13.3	.....	12.1	11.6
3 pecks	.....	7.5	12.1	.....	14.5	11.5	.....	11.4	10.7
4 pecks	13.7	9.7	12.2	.....	16.0	12.5	.....	12.8	11.8
5 pecks	.....	8.8	12.2	.....	16.1	11.1	.....	12.1	10.8
6 pecks	.....	9.8	11.0	.....	18.6	11.3	.....	12.7	11.2
7 pecks	.....	10.3	12.1	.....	19.3	11.5	.....	13.3	11.6
8 pecks	.....	10.5	11.5	.....	20.3	12.1	.....	13.6	11.6
Intermediate date:									
2 pecks	14.7	9.1	11.8	5.0	21.2	.....	16.0	13.0	12.5
3 pecks	16.8	8.8	10.9	4.2	23.6	.....	15.8	13.4	12.7
4 pecks	15.8	10.7	11.2	5.7	24.3	.....	14.8	13.8	12.8
5 pecks	16.0	9.0	10.5	5.5	24.8	.....	14.7	13.4	12.1
6 pecks	18.3	9.0	11.0	4.9	25.3	.....	15.3	14.0	12.5
7 pecks	14.7	8.7	10.2	5.7	24.8	.....	15.3	13.2	11.5
8 pecks	15.7	8.8	10.2	5.4	24.1	.....	14.5	13.1	11.1
Late-fall date:									
2 pecks	10.0	7.0	11.0	2.5	22.6	4.3	.....	9.6	9.1
3 pecks	12.2	9.3	11.4	3.0	26.7	5.0	.....	11.3	10.6
4 pecks	11.8	10.5	11.5	3.4	25.7	6.5	.....	11.6	10.6
5 pecks	13.8	10.5	10.8	3.3	25.3	7.8	.....	11.9	10.7
6 pecks	13.3	10.8	10.8	3.7	25.1	8.8	.....	12.1	10.6
7 pecks	13.3	11.5	10.0	3.4	23.5	8.5	.....	11.7	10.0
8 pecks	14.0	10.1	10.0	3.9	24.5	8.5	.....	11.8	9.8

[1] After deducting seed.

Variations in yields have shown very little relation to the variations in rate of seeding; and had individual plot rather than yearly average yield data been given, the results would have shown even less consistency. Apparently the condition of the seed bed and growing season and other factors have more influence than rate of seeding. The data do not point conclusively to any rate as being best for any particular condition, but they do suggest the 4-peck rate as the best average net rate for varying conditions over a period of years; and since farm practice is based on the 4-peck rate of seeding, the experimental evidence tends to confirm this practice.

SPRING WHEAT

At Lind the experiments with spring wheat to determine the best rates and dates of seeding included the rate factor on only the first date. The date of first seeding in the spring was determined by seasonal conditions and varied from February 26 in 1925 to March 17 in 1923. In any case, the first seeding date was always the earliest date in spring at which seeding could be done. It averaged March 10, although being later than that in 7 of the 13 years. The two later dates were based on the apparent rapidity of advance of the season, but were at approximate intervals of one month after the first. The results are presented in Table 36.

TABLE 36.—*Annual and average yields of Baart spring wheat in date-of-seeding experiments at Lind, Wash., 1918–1930*

Time of seeding	Acre yield (bushels)													
	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	Average
Early	6.6	10.4	10.3	8.9	6.3	22.9	10.4	16.2	17.1	16.8	16.5	11.3	4.1	12.1
Intermediate	5.3	10.0	9.9	7.5	5.6	21.5	10.5	13.5	13.7	12.2	16.1	10.8	5.0	10.9
Late	3.3	8.0	8.6	4.9	5.0	17.9	6.1	9.9	8.7	15.8	13.6	9.1	7.6	9.1

These data point conclusively to the advantages of early seeding for spring wheat.

For average conditions the rate of seeding does not seem to be a particularly important factor so long as the rate is heavy enough to provide a stand capable of competing with weeds. The results of rate-of-seeding experiments with spring wheat are given in Table 37. These data indicate that a rate of 3 to 5 pecks gives the best average net yield, and that under usual conditions increases beyond this rate, although perhaps aiding in competing with weeds and wireworms, do not increase the net yield.

TABLE 37.—*Annual and average net yields of Baart spring wheat in rate-of-seeding experiments at Lind, Wash., 1917–1926*

Rate of seeding	Acre yield (bushels)										
	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	Average
2 pecks	5.2	6.8	7.0	9.6	3.0	7.7	25.9	8.8	18.0	15.9	10.8
3 pecks	7.2	6.5	9.3	10.5	4.0	7.1	24.6	9.8	18.3	14.9	11.2
4 pecks	8.4	5.6	9.4	9.3	7.7	6.1	23.1	9.1	17.7	14.3	11.1
5 pecks	8.0	4.4	9.1	9.6	7.4	6.4	21.8	9.6	19.1	13.5	10.9
6 pecks	7.7	5.0	9.1	8.1	8.0	5.7	21.0	7.8	18.0	13.5	10.4
7 pecks	7.6	3.7	9.4	7.9	8.8	5.2	18.3	7.8	17.5	12.8	9.9
8 pecks	7.2	3.3	9.8	7.2	8.5	4.6	19.4	7.2	16.8	11.8	9.6

RESULTS AT NEPHI

A rate-of-seeding experiment was conducted at Nephi from 1910 to 1920, inclusive, with Turkey and Kofod winter wheats. Beginning in 1921, however, the rate trial was replaced by a combination rate-and-date-of-seeding experiment in which wheat was sown at rates from 2 to 8 pecks on August 1 and 15, September 1 and 15, October 1 and 15, and November 1. The yearly yields from 1921 to 1929, inclusive, are presented in Table 38 for all rates and dates of seeding.

TABLE 38.—*Annual and average yields of winter wheat in rate-and-date experiments conducted at Nephi, Utah, 1921–1929*

Date and rate of seeding	Acre yield (bushels)										
	1921	1922	1923	1924	1925	1926	1927	1928	1929	Average	
										Actual	Net [1]
Aug. 1:											
2 pecks	22.0	1.3	11.0	12.0	38.7	35.0	14.7	20.0	8.7	18.2	17.7
3 pecks	32.4	3.3	17.3	13.7	35.7	32.0	14.3	20.0	9.7	19.8	19.0
4 pecks	46.7	5.0	19.7	15.3	37.7	36.7	10.6	21.3	13.0	22.9	21.9
5 pecks	43.7	4.3	12.0	13.7	30.3	30.0	9.3	18.3	15.0	19.6	18.3
6 pecks	45.3	3.7	16.3	14.7	29.0	32.7	9.0	21.0	14.3	20.7	19.2
7 pecks	44.3	4.0	13.7	13.7	27.2	33.0	9.3	20.7	15.7	20.2	18.4
8 pecks	44.0	4.3	11.3	13.0	27.3	32.0	10.7	19.3	17.3	19.9	17.9
Average	39.8	3.7	14.5	13.7	32.3	33.1	11.1	20.1	13.4	20.2	.....
Aug. 15:											
2 pecks	34.0	2.0	8.0	10.7	22.8	28.0	10.0	17.3	13.7	16.3	15.8
3 pecks	37.7	2.7	11.3	10.7	24.7	32.3	11.0	20.3	16.7	18.6	17.8
4 pecks	40.0	5.0	14.0	14.3	25.0	40.7	9.7	20.3	17.0	20.7	19.7
5 pecks	40.3	4.0	14.3	16.3	29.5	40.3	11.3	21.0	19.0	21.8	20.5
6 pecks	43.0	3.7	14.7	16.7	27.2	41.1	11.3	20.7	19.1	21.9	20.4
7 pecks	42.0	3.7	16.3	15.3	25.0	40.0	9.0	21.3	15.3	20.9	19.1
8 pecks	44.0	4.0	13.3	17.3	21.5	40.0	9.0	20.3	15.6	20.6	18.6
Average	40.1	3.6	13.1	14.5	25.1	37.5	10.2	20.2	16.6	20.1	.....
Sept. 1:											
2 pecks	33.0	2.0	12.0	12.0	18.7	35.3	6.0	19.0	14.7	17.0	16.5
3 pecks	38.3	4.3	11.3	13.7	17.2	35.7	7.3	20.0	18.7	18.5	17.7
4 pecks	38.3	6.6	12.0	17.0	18.8	43.3	8.7	17.3	17.3	19.9	18.9
5 pecks	37.0	8.0	12.3	17.0	20.5	42.7	9.6	24.0	19.7	21.2	20.0
6 pecks	32.0	11.0	14.0	17.7	17.2	43.3	9.6	21.7	19.3	20.6	19.1
7 pecks	24.0	11.3	14.7	17.7	20.3	45.3	9.6	21.3	18.7	20.3	18.5
8 pecks	30.2	12.0	15.0	20.0	22.0	46.0	9.7	22.7	16.0	21.5	19.5
Average	33.3	7.9	13.0	16.4	19.2	41.7	8.6	20.9	17.8	19.9	.....
Sept. 15:											
2 pecks	22.7	4.0	12.3	15.3	19.0	40.0	9.7	20.0	13.7	17.4	16.9
3 pecks	27.5	7.3	16.7	15.7	20.7	42.0	11.7	23.0	17.7	20.3	19.5
4 pecks	30.3	8.3	19.0	18.3	27.5	42.3	13.0	25.7	19.3	22.6	21.6
5 pecks	37.2	8.7	20.2	18.0	29.7	40.7	14.3	24.0	15.3	23.1	21.8
6 pecks	40.3	8.7	22.3	19.0	29.2	41.0	14.7	23.7	17.7	24.1	22.6
7 pecks	41.2	9.0	25.0	18.7	31.0	37.3	15.3	23.0	19.0	24.4	22.6
8 pecks	43.2	10.3	25.3	18.0	29.5	41.0	15.3	19.0	20.3	24.7	22.7
Average	34.6	8.0	20.1	17.6	26.7	40.6	13.4	22.6	17.6	22.4	.....
Oct. 1:											
2 pecks	34.7	2.7	20.7	16.7	28.7	26.7	8.7	22.3	18.0	19.9	19.4
3 pecks	33.0	4.3	20.0	16.7	32.3	30.0	13.3	26.0	16.3	21.3	20.4
4 pecks	36.3	6.0	21.8	18.0	30.0	34.7	10.7	30.0	19.0	22.9	21.9
5 pecks	35.3	8.3	22.3	20.7	35.0	33.7	13.7	26.7	24.0	24.4	23.1
6 pecks	35.7	5.1	23.3	19.3	29.3	35.0	13.3	31.0	23.3	23.9	22.4
7 pecks	40.0	12.0	23.3	18.7	30.0	32.3	17.3	26.7	20.7	24.6	22.8
8 pecks	39.7	11.3	22.3	21.0	32.0	34.3	14.3	29.3	19.3	24.8	22.8
Average	36.4	7.1	22.0	18.7	31.0	32.4	13.0	27.4	20.1	23.1	.....
Oct. 15:											
2 pecks	34.2	2.7	16.3	16.3	28.0	30.3	15.7	23.3	14.7	20.2	19.7
3 pecks	29.5	2.7	17.7	16.7	28.0	33.3	13.0	25.7	23.0	21.1	20.3
4 pecks	33.0	3.0	20.7	15.7	29.8	34.0	15.7	21.3	21.3	21.6	20.6
5 pecks	37.8	3.3	23.7	12.7	32.0	29.0	16.0	24.3	23.7	22.5	21.2
6 pecks	38.5	6.0	22.7	13.3	31.0	32.7	12.7	26.0	21.3	22.7	21.2
7 pecks	39.3	10.7	22.0	12.7	27.3	31.7	17.3	27.3	24.0	23.6	21.8
8 pecks	37.5	9.3	24.7	14.7	31.3	35.0	13.3	25.0	21.0	23.5	21.5
Average	35.7	5.4	21.1	14.6	29.6	32.3	14.8	24.7	21.3	22.2	.....
Nov. 1:											
2 pecks	32.7	1.0	16.6	8.0	26.5	29.3	13.0	24.0	16.7	18.6	18.1
3 pecks	37.3	4.0	16.0	15.3	23.3	32.7	14.7	32.0	21.7	21.9	20.1
4 pecks	37.3	5.7	17.0	17.0	28.0	33.0	15.7	26.7	22.0	22.5	21.5
5 pecks	38.3	8.3	17.7	16.7	24.0	32.7	18.7	30.7	20.0	23.0	21.8
6 pecks	40.7	9.3	19.3	19.3	27.0	36.0	20.0	26.7	24.0	24.7	23.2
7 pecks	37.8	8.3	20.0	20.7	27.7	35.0	20.0	32.0	21.7	24.8	23.0
8 pecks	36.8	10.2	18.0	20.3	29.3	37.0	18.0	32.3	22.0	24.9	22.9
Average	37.3	6.7	17.8	16.8	26.5	33.7	17.2	29.2	21.2	22.9	.....

[1] After deducting seed.

The data in Table 38 show wide fluctuations in yields. High yields of winter wheat in the Great Basin usually are associated with fall

emergence of the crop and low yields with emergence under winter snow, provided poor or untimely tillage is not a factor causing reduction. The normal or better than normal yields of 1921, 1925, 1926, and 1928, as shown in Table 38, occurred in seasons when the crop emerged in the fall, and the low yields of 1922, 1923, 1927, and 1929 occurred in seasons when the crop did not emerge until winter. April temperature also has a direct influence on yield. If the crop emerges in the fall early enough to establish permanent roots, below-normal temperatures in April have no noticeable effect on yield. On the other hand, if the crop fails to tiller before spring, below-normal temperatures in April force all vegetative production into the longer, hot, drying days of late spring and early summer, with the consequence that yields usually are materially reduced.

As the data indicate, there is little difference in yield between sowings made on August 1, August 15, and September 1. Between September 1 and 15 there is an increase of 2.4 bushels in favor of the later sowings.

Heavy torrential showers sometimes occur in the Great Basin until about September 10. These storms frequently result in a crusting of the surface of the clay-loam soils, often preventing grain from emerging. A part of the lower yields from early seeding can be attributed to this factor. After September 10, the storms more often come as gentle rains and have little detrimental effect on the physical condition of the soil. At times there is sufficient moisture in the surface soil at the end of the summer period to start germination. If a long dry period follows, many young plants may die, thus accounting for a part of the yield reduction from early seeding. With sufficient moisture to allow uniform germination and continued growth, August or early seeding at Nephi will normally give higher yields than later seeding. With the soil in the seeding zone too dry for germination, it is advisable to delay seeding until the last of September or the first part of October.

The detailed data and the averages in Table 38 show a decided advantage in sowing 4 pecks or more of seed to an acre, as compared to lower rates. Sowings made on October 1, the date that has given the highest yield for all rates of seeding, also indicate a decided advantage for the higher rates.

The data in Table 39 are averages of all dates of seeding for each rate with actual and net yields. Considering the actual yields, a gradual increase is shown with increased rates up to 6 pecks. From 6 to 8 pecks the differences in yield are so small as to be negligible. The results in the net yield column indicate that the highest returns are secured from 5 and 6 pecks, with no advantage for heavier seeding.

TABLE 39.—*Average yields of winter wheat sown on all dates of seeding for every 15 days from August 1 to November 1, inclusive, for each of seven rates of seeding at Nephi, Utah, 1921–1929*

Rate of seeding	Acre yield (bushels)		Rate of seeding	Acre yield (bushels)	
	Actual	Net [1]		Actual	Net [1]
2 pecks	18.2	17.7	6 pecks	22.7	21.2
3 pecks	20.2	19.4	7 pecks	22.7	20.9
4 pecks	21.9	20.9	8 pecks	22.8	20.8
5 pecks	22.2	21.0			

[1] After deducting seed.

DEPTH OF SEEDING EXPERIMENTS

RESULTS AT MORO

The stand of winter wheat may be greatly influenced by the depth of sowing. Better germination of winter wheat usually is obtained from shallow seeding, especially if the wheat is sown very late when the ground is cold. As it generally is desirable to have a comparatively thick stand of winter wheat, farmers in the Columbia Basin usually sow wheat from 1½ to 3 inches deep.

Experiments to determine the effect on yield of different depths of sowing winter wheat were conducted at Moro, Oreg., and Lind, Wash. At Moro wheat was sown 2 and 4 inches deep in duplicate plots at 5 pecks per acre on August 26, 1914, before the autumn rains. One plot was sown with seed treated with formaldehyde and the other with untreated seed. The experiment was repeated on September 9. On both dates of sowing an irregular stand was obtained on the plots sown 4 inches deep. On November 5 counts were made of plants emerged on representative areas on each plot, and the results obtained are shown in Table 40.

TABLE 40.—*Stand of plants per acre in depth-of-seeding experiments at Moro, Oreg., in 1914*

Time of seeding and treatment	Depth of sowing	
	Shallow	Deep
Early seeding:		
Seed treated	83,000	37,000
Seed not treated	180,000	84,000
Late seeding:		
Seed treated	104,000	62,000
Seed not treated	140,000	120,000
Average	126,750	75,750

The average yield obtained from the shallow seeding was 17.3 bushels per acre and from the deep seeding 14.9 bushels per acre. The yields, however, were somewhat influenced by weeds, which were numerous in the thin irregular stand obtained from deep seeding.

Table 41 shows the yields obtained from sowing winter wheat at depths of 2, 3½, and 5 inches in the four years 1917, 1918, 1919, and 1921. Sowings were made in duplicate twentieth-acre plots each year. On account of favorable moisture and temperature conditions at the time of sowing, practically no difference was obtained in the stands from the three depths of seeding during any of the years. It will be noted from Table 41 that the average yields obtained from the three depths of seeding were practically identical, indicating that the depth of seeding probably has no influence on the yield if uniform stands are obtained.

TABLE 41.—*Annual, total, and average yields of Turkey winter wheat sown at three depths at Moro, Oreg., 1917–1921, omitting 1920*

Depth of seeding	Acre yield (bushels)					
	1917	1918	1919	1921	Total	Average
Shallow, 2 inches	20.8	26.3	18.6	37.0	102.7	25.7
Middeep, 3½ inches	22.0	24.3	19.6	39.8	105.7	26.4
Deep, 5 inches	22.2	24.7	20.1	38.6	105.6	26.4
Total	65.0	75.3	58.3	115.4	314.0	
Average	21.7	25.1	19.4	38.5		26.2

RESULTS AT LIND

WINTER WHEAT

At Lind, depth-of-seeding experiments were carried parallel to the rate-and-date-of-seeding experiments with both fall and spring wheats. Data for the depth-of-seeding experiments with winter wheat are given in Table 42.

TABLE 42.—*Annual stands and yields of Turkey winter wheat sown on three different dates in depth-of-seeding experiments at Lind, Wash., 1919–1922*

Time and depth of seeding	1919		1920		1921		1922	
	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield
Early date:		*Bush.*		*Bush.*		*Bush.*		*Bush.*
1 inch	220,000	15.8	128,000	9.2	624,000	12.1		
2½ inches	122,000	13.7	76,000	6.5	756,000	11.9		
4 inches	64,000	9.0	53,000	5.0	819,000	12.2		
Midseason date:								
1 inch	380,000	16.9	164,000	9.8	804,000	10.8	406,000	5.6
2½ inches	237,000	16.2	93,000	7.0	844,000	11.7	249,000	5.3
4 inches	166,000	12.6	83,000	6.1	751,000	11.7	281,000	5.0
Late date:								
1 inch	375,000	13.9	180,000	10.5	999,000	11.1	131,000	3.3
2½ inches	358,000	12.6	135,000	9.9	901,000	10.7	125,000	3.7
4 inches	289,000	13.9	147,000	8.8	852,000	10.8	108,000	3.0

[1] Plants per acre.

In interpreting these data it must be borne in mind that conclusions based on them are applicable only to conditions similar to those prevailing during the period of the experiments. In the fall of 1918 and in 1919 and 1921 the seed either remained dormant in the dry soil to be germinated at a later date or it was seeded at the later date under conditions where the soil, even at the shallow depth, remained moist after seeding. For such conditions the most shallow seeding was the best. In the fall of 1920, on the other hand, there was some early moisture, followed later by dry weather. In these conditions, deeper seeding was better except on the very late seeding. The best depth of seeding, therefore, must be determined by conditions.

SPRING WHEAT

Conditions prevailing at the time spring wheat is sown differ somewhat from those found in the fall when winter wheat is seeded. In the spring the soil is moist; but if the season is dry, it may tend to dry more or less rapidly from the surface downward. Data on depth-of-seeding experiments with spring wheat are given in Table 43.

TABLE 43.—*Annual and average yields of Baart spring wheat in depth-of-seeding experiments at Lind, Wash., 1917–1922*

Depth of seeding	Acre yield (bushels)						
	1917	1918	1919	1920	1921	1922	Average
1 inch	9.4	5.3	9.7	9.6	7.5	7.1	8.1
2½ inches	9.4	6.2	10.4	10.6	8.7	7.4	8.8
4 inches	9.9	6.4	11.2	10.5	9.1	7.8	9.2

These data are distinctly in favor of the deepest seeding. In a season when precipitation is comparatively abundant at the time of seeding, as in 1917, the most shallow seeding may be practically equal to that at the greater depths; but for the drier conditions, on the average, the deep seeding is preferable for spring wheat.

SPACING AND FURROW-SEEDING EXPERIMENTS

RESULTS AT MORO

Experiments to determine the effect on yield of sowing wheat in rows spaced different distances apart were conducted at Moro with spring and with winter wheat. Table 44 shows the yields obtained from sowing Turkey winter wheat in rows 7 and 14 inches apart in the years 1917 to 1924, inclusive. Duplicate sowings on twentieth-acre plots were made in each of these years except 1919, when the experiment was repeated four times on twentieth-acre plots. Exactly the same quantity of seed was sown on each plot, the rows 14 inches apart having twice the quantity of seed per row as the rows 7 inches apart. Wheat sown thickly in the row usually emerged more quickly than wheat sown thinly. Thickly sown wheat also grows more rapidly when the plants are young. It will be noted from Table 44 that the average acre yield obtained from the 14-inch spacing is 2 bushels less than that obtained from the 7-inch spacing. This difference in yield is significant and indicates that maximum yields of winter wheat can not be obtained by sowing in rows spaced as widely as 14 inches apart.

TABLE 44.—*Annual, total, and average yields of Turkey winter wheat sown in rows 7 inches and 14 inches apart at Moro, Oreg., 1917–1924*

Spacing	Acre yield (bushels)									
	1917	1918	1919	1920	1921	1922	1923	1924	Total	Average
7 inches	20.0	23.0	30.7	26.0	36.7	16.3	28.7	9.7	191.1	23.9
14 inches	18.5	20.5	26.7	23.7	34.8	16.2	26.2	8.7	175.3	21.9

In Table 45 are shown yields for two fall-sown wheat varieties, Federation and Turkey, sown at Moro with a 6-inch double-disk drill and a 12-inch furrow drill, for the years 1927 to 1929, inclusive. In 1927 and 1928 a Van Brunt furrow drill was used, and in 1929 a Van Brunt and a Superior furrow drill were used. The advantages claimed for the furrow drill are protection from winterkilling and quicker emergence. The results for the three years show a slight increase in yield from the furrow-drill seeding for Federation wheat, a nonwinter-hardy variety, and a decrease in yield for Turkey wheat, a winter-hardy variety.

TABLE 45.—*Annual and average yields of Federation and Turkey winter wheat sown in the fall with a double disk and a furrow drill at Moro, Oreg., 1927–1929*

Type of drill	Acre yield (bushels)							
	1927		1928		1929		Average	
	Federation	Turkey	Federation	Turkey	Federation	Turkey	Federation	Turkey
Double-disk drill (6-inch spacing)	44.5	42.5	40.3	40.2	11.4	10.8	32.1	31.2
Furrow drill (12-inch spacing)	46.9	43.4	38.8	36.9	16.4	10.5	34.0	30.3

In 1916 and 1917 an experiment was conducted to determine the effect on yield of spring wheat and winter wheat of sowing in rows 4, 6, and 8 inches apart. In 1916 wheat also was sown in paired rows 6 inches apart, with a 24-inch spacing between the adjacent pairs. The experiment was conducted on small plots 8 feet wide and 33 feet long. Duplicate plots were sown at each of three rates of seeding, namely, 4, 5, and 6 pecks per acre, on each of the four different spacings. An equal quantity of seed was sown in each of the four different spacings in each rate. The yields obtained in 1916 from each plot are shown in Table 46.

TABLE 46.—*Yields of Pacific Bluestem spring wheat when sown at three different rates and at four different distances between rows at Moro, Oreg., in 1916*

Rate of seeding	Yield per plot (pounds)							
	Single rows						Paired rows, 6 inches apart, 24-inch spacing between pairs	
	4-inch spacing		6-inch spacing		8-inch spacing			
	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2
4 pecks	7.00	8.50	8.00	11.50	7.50	5.00	5.25	4.00
5 pecks	10.25	10.50	9.25	10.50	9.50	8.75	4.50	4.00
6 pecks	10.00	11.00	9.50	9.00	8.50	8.50	4.50	4.50
Average	9.54		9.63		7.96		4.46	

In 1917 this experiment was repeated, except that the wheat was sown in rows 4, 6, 8, and 12 inches apart and two varieties were used. The yields of grain of Kharkof and of Pacific Bluestem, in pounds per plot, are shown in Table 47.

TABLE 47.—*Yields of Kharkof winter wheat and Pacific Bluestem spring wheat when sown at three different rates and at four different distances between rows at Moro, Oreg., in 1917*

Variety and rate of seeding	Yield per plot (pounds)							
	4-inch spacing		6-inch spacing		8-inch spacing		12-inch spacing	
	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2
Kharkof:								
4 pecks	8.0	8.0	8.5	6.0	6.0	8.0	7.0	9.0
5 pecks	7.0	8.0	7.0	7.0	5.0	6.5	7.0	6.0
6 pecks	6.0	9.0	5.0	8.0	4.0	8.5	5.0	6.5
Average	7.7		6.9		6.3		6.7	
Pacific Bluestem:								
4 pecks	3.0	4.0	4.0	3.5	2.0	3.5	2.0	3.0
5 pecks	4.0	4.5	3.5	4.5	3.5	4.0	3.0	4.0
6 pecks	3.0	4.0	4.5	4.0	3.5	4.5	2.0	4.0
Average	3.8		4.0		3.5		3.0	

In 1916 the highest yields were obtained from the 4-inch and 6-inch spacings with Pacific Bluestem wheat, as is shown in Table 46. In 1917 slightly higher yields of Kharkof wheat were obtained from the 4-inch spacing, with the yields from the 6, 8, and 12-inch spacings practically identical, as shown in Table 47. There also was not a wide variation in the yields obtained in 1917 from the Pacific Bluestem sown with the 4, 6, 8, and 12 inch spacings. The 12-inch spacing gave the lowest yield and the 6-inch spacing the highest, as also shown in Table 47.

RESULTS AT LIND

Furrow-seeding experiments were started at Lind on one-fortieth acre plots in the fall of 1920. The furrows were made 14 inches apart with a hand plow and sown with a garden drill. The nonfurrowed plots were sown with a 16–7 hoe drill. For the three crops from 1921 to 1923, inclusive, the seedings were made in soil so dry that emergence was not complete until midwinter or early spring, and there was no opportunity to observe the influence of the furrows on winter survival. Turkey winter wheat was used, and the results are given in Table 48. They do not indicate any particular advantage for the furrows.

TABLE 48.—*Annual and average stands and yields of Turkey winter wheat grown in furrowed and unfurrowed one-fortieth acre plots at Lind, Wash., 1921–1923*

Treatment	1921		1922		1923		Average	
	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield	Stand [1]	Acre yield
		Bushels		*Bushels*		*Bushels*		*Bushels*
Furrowed	282,000	8.5	266,000	4.6	86,000	20.0	211,000	11.0
Not furrowed	462,000	8.4	372,000	5.2	233,000	20.4	356,000	11.3

[1] Plants per acre.

In the fall of 1926 the furrows in the furrow-seeding experiment were made 14 inches apart with double-disk furrowing attachments for a Van Brunt 18–7 drill. The nonfurrowed plots were sown with the same drill without the furrowing attachments. Direction of seeding was both east and west and north and south. The sowings were

made with Jones Fife winter wheat in a moist seed bed on October 8, and the seedlings emerged promptly. The following winter was mild; and although Jones Fife wheat often shows winter injury, there was none in this experiment, and again the influence of the furrows on winter survival could not be measured. The results are given in Table 49. The data suggest that when a stand can be obtained with an ordinary hoe drill there is no advantage in yield to be obtained with the furrow drill.

TABLE 49.—*Stands and yields of Jones Fife winter wheat grown in one-tenth acre plots in a furrow-seeding experiment at Lind, Wash., in 1927*

Direction of seeding and soil treatment	Stand [1]		Acre yield
	Plants	Culms	
East and west:			*Bushels*
Furrowed	309,000	627,000	20.0
Not furrowed	407,000	648,000	23.3
North and south:			
Furrowed	341,000	424,000	21.4
Not furrowed	476,000	584,000	30.0

[1] Number per acre.

Furrow seedings were also made for the crops of 1929 and 1930; but because the seed bed was dry and no rains followed the seeding operations, stands were not obtained. In all furrow-seeding experiments stands of winter wheat have not been obtained with the deep-furrowing drills when they could not also be obtained with the ordinary 7-inch hoe drill. The moisture for seed germination has always come from timely precipitation; and because yields have been slightly in favor of the ordinary drill the conclusion has been reached that the furrow drills do not offer much advantage over the ordinary drill for sowing winter wheat at this station.

Row-spacing experiments were conducted with spring wheat in 1924, 1925, and 1926, and with winter wheat in 1926. They were sown with a 16–7 hoe drill, and in the wide-spaced rows the seed tubes of adjacent hoes were set to feed into the seeding hoe. Thus the surface was left comparable after seeding, and the only variable was the spacing of the rows, each or every third one having seed in it. The heavy rate of seeding was intended to give as thick a distribution of plants per foot of row in the 7-inch spacing as the light rate of seeding did in the 21-inch spacing. The results are given in Table 50.

TABLE 50.—*Annual stands and yields of Baart spring wheat and Turkey winter wheat in a row-spacing experiment at Lind, Wash., for stated years*

Spacing of rows	Rate of seeding per acre	Baart spring wheat									Turkey winter wheat, 1926		
		1924			1925			1926					
		Stand [1]		Acre yield	Stand [1]		Acre yield	Stand [1]		Acre yield	Stand [1]		Acre yield
		Plants	Culms		Plants	Culms		Plants	Culms		Plants	Culms	
	Pecks			*Bush.*			*Bush.*			*Bush.*			*Bush.*
7 inches	3	------	370	9.7	289	788	17.1	130	273	14.8	266	408	12.8
21 inches	3	------	304	9.7	226	542	14.2	189	543	13.6	106	482	12.4
7 inches	8	------	322	8.3	678	887	18.2	279	423	13.1	315	492	13.4
21 inches	8	------	------	------	440	860	15.8	294	747	13.4	151	475	12.4

[1] Thousands per acre.

The precipitation in the growing seasons of 1924 and 1926 was below average, and the plants made most of their growth on reserve soil moisture. Under those conditions row spacing as wide as 21 inches influenced the yields only slightly. In 1925 the reserve soil moisture

FIGURE 29.—Baart spring wheat sown in 21-inch rows at the Adams Branch Station, Lind, Wash., 1925

was below average and the growing season precipitation above average. Then the wide spacing reduced the yield. The stands of both plants and culms varied much more than the yields.

FIGURE 30.—Baart spring wheat sown in 7-inch rows at the Adams Branch Station, Lind, Wash., 1925

Spring wheat sown in 21-inch rows and in 7-inch rows at Lind, Wash., is shown in Figures 29 and 30. In Figure 31 are shown plots

of winter wheat sown with a furrow drill and with an ordinary drill at Moro, Oreg.

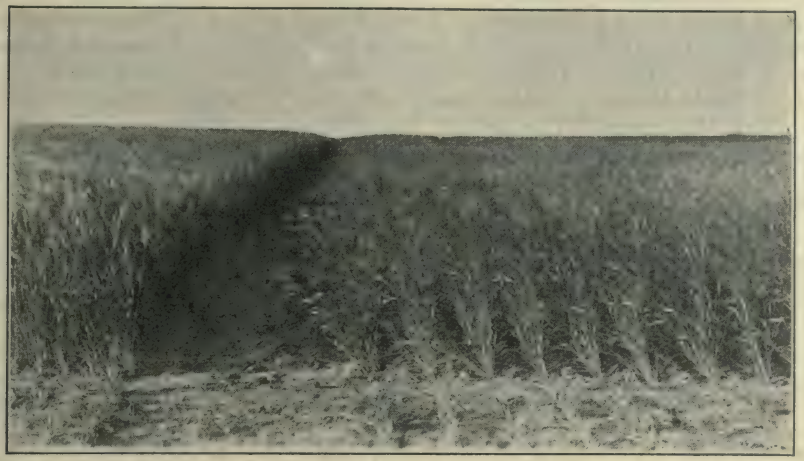


FIGURE 31.—Turkey winter wheat sown with a 12-inch furrow drill (right) and with a 6-inch ordinary drill (left) at the Sherman County Branch Station, Moro, Oreg., 1927

RESULTS AT NEPHI

The spacing experiment at Nephi was conducted to determine the effect of sowing winter wheat in rows at various distances apart. As is shown in Table 51, the rows were spaced 7, 14, 21, and 28 inches apart. One set of plots was left uncultivated and the other was cultivated in the spring when the wheat was about 4 inches high. The experiment was conducted on duplicate twentieth-acre plots. The data in Table 51 show only slight variation in yields of wheat for rows spaced 14, 21, and 28 inches. The normal drill width (7 inches) in each case, uncultivated and cultivated, produced yields 2 to 3 bushels higher than those obtained from the wider spacings.

TABLE 51.—*Annual and average yields of Kanred winter wheat when sown in rows spaced different distances apart, with one set of plots uncultivated and one set cultivated, in the spring of the cropped year, at Nephi, Utah, 1923–1929*

Spacings	Acre yield (bushels)							
	1923	1924	1925	1926	1927	1928	1929	Average
Uncultivated:								
7 inches	27.5	23.1	40.1	37.0	18.9	32.8	21.1	28.6
14 inches	24.6	22.2	34.2	38.7	17.5	30.2	21.0	26.9
21 inches	21.8	23.8	31.1	36.8	20.2	30.0	20.3	26.3
28 inches	.....	22.1	31.7	31.1	16.0	30.6	24.5	26.0
Average	24.6	22.8	34.3	35.9	18.2	30.9	21.7	26.9
Cultivated:								
7 inches	22.1	21.7	35.9	38.7	19.5	37.5	18.3	27.7
14 inches	20.8	19.0	29.8	35.3	17.2	33.5	17.3	24.7
21 inches	19.7	22.2	27.4	34.3	18.0	32.5	21.8	25.1
28 inches	.....	21.9	24.3	34.1	16.5	28.3	20.6	24.3
Average	20.9	21.2	29.4	35.6	17.8	33.0	19.5	25.4

The furrow drill, which has been recommended for areas of the Great Plains for sowing winter wheat, was tried at Nephi from 1923 to 1929, inclusive. One of the problems on the dry lands of the Great Basin is to get stands of grain before winter. Often sufficient moisture to germinate grain is held in the fallow land about 6 inches below the surface. It was thought that by using the furrow drill wheat could be sown in this moist soil, thus allowing a quicker emergence of the grain. The results from furrow sowings, together with those from the ordinary drill, are given in Table 52. A comparison of the averages fails to indicate any advantage in favor of the furrow drill except in seasons of very low rainfall, such as 1924.

TABLE 52.—*Annual and average yields of winter wheat sown on triplicated twentieth-acre plots with the ordinary drill and the furrow drill at Nephi, Utah, 1923–1929*

Type of drill	Acre yield (bushels)							
	1923	1924	1925	1926	1927	1928	1929	Average
Ordinary drill	31.4	24.0	37.0	32.4	18.3	29.3	21.2	27.7
Furrow drill	28.4	27.6	36.2	31.9	17.8	27.1	20.2	27.0

SUMMARY

Wheat is one of the most important farm crops grown in Oregon, Washington, Utah, and Idaho, and is the only important commercial crop grown on the nonirrigated lands. Successful dry-farm wheat production in these States is based on alternate years of crop and clean fallow.

Experiments to determine the effect of different tillage methods on the yield of wheat were begun at Nephi, Utah, in 1904, at Moro, Oreg., in 1911, and at Lind, Wash., in 1916, by the agricultural experiment stations of these States in cooperation with the United States Department of Agriculture.

The altitude at Moro is 1,800 feet and the soil a silt loam. The altitude at Lind is 1,600 feet and the soil a fine sandy loam. At Nephi the altitude is 5,300 feet and the soil a heavy clay loam.

The average annual precipitation at Moro is 11.46 inches; at Lind, 7.82 inches; and at Nephi, 13.02 inches.

The average evaporation from a free water surface at Moro in the 6-month period April to September, inclusive, was 43.41 inches; at Nephi, 43.81 inches; and at Lind, 46.03 inches.

The average frost-free period at Moro is 147 days, at Lind 144 days, and at Nephi 113 days.

The fall disking of stubble land plowed early in the spring for fallow decreased winter-wheat yields at Moro, Lind, and Nephi. Disking stubble land in the spring before plowing increased yields at Moro and at Lind when the plowing was done as late as June 1, but did not increase yields when the plowing was completed by May 1. Yields of winter wheat after fall-plowed fallow when the stubble was burned and when different quantities of stubble were turned under were almost identical over a 14-year period at Nephi. At Moro slightly higher yields were obtained where all the straw was plowed under for a 7-year period.

Early spring plowing gave the highest yields of winter wheat at Moro. The average yields of eight tenth-acre plots plowed at different times were:

	Bushels per acre
Fall plowing, early (dry)	26. 3
Fall plowing, late (wet)	25. 1
Early spring plowing (April 1)	28. 8
Late spring plowing (May 1)	27. 0
Early summer plowing (June 1)	22. 9

The average yields of spring and winter wheat in a 13-year period at Lind were:

	Bushels per acre
Fall plowing (dry)	12. 2
Fall plowing (wet)	12. 8
Early spring plowing (March)	13. 9
Late spring plowing (April)	13. 5
Early summer plowing (June)	11. 5

The average yields of Turkey winter wheat at Nephi for the 14-year period from 1916 to 1929, inclusive, were:

	Bushels per acre
Fall plowing	23. 5
Early spring plowing	24. 4
Late spring plowing	17. 9
Early summer plowing	14. 5

In depth-of-plowing experiments at Moro in the 17 years 1912 and 1914 to 1929, inclusive, the average acre yield of eight tenth-acre plots of spring wheat and winter wheat plowed early in the spring 5 inches deep was 21.4 bushels, and the average yield of eight tenth-acre plots plowed on the same dates 10 inches deep was 22.1 bushels per acre. Disking about 3 inches deep for fallow at Moro for a 5-year period produced yields of wheat as high as plowing 8 inches deep.

In depth-of-plowing experiments at Lind the yields from 4-inch and 6-inch depths were nearly the same on both wet and dry fall plowing. On the early spring plowing the yields from all depths averaged nearly the same. On the late spring plowing the average yields were slightly in favor of the deeper plowing. On the early summer plowing the average yields from shallow and deep plowing were the same.

At Nephi the average yield of winter wheat in the 14 years from 1916 to 1929, inclusive, on land fall plowed 8 inches deep was 3.0 bushels per acre greater than that obtained on land fall plowed 5 inches deep. The yields from 8-inch and 10-inch plowing were slightly higher than those obtained from subsoiling 15 to 18 inches deep. Plowing in the fall and replowing in the spring did not increase winter-wheat yields over those from one plowing.

Packing land with surface or subsurface packers after plowing at Moro did not materially increase the yields of winter or spring wheat. On land plowed early in the spring, slightly higher yields were obtained at Lind on land packed with a packer. On land plowed in April, the yields at Lind also have slightly favored the plots packed after plowing, while on June-plowed plots the reverse was true.

Frequent cultivation of the summer fallow at Moro resulted in higher average yields of winter wheat on fall-plowed land or on land

plowed April 1 and May 1 than no cultivation of the fallow or one harrowing only. Where plowing was done as late as June 1, cultivation of the summer fallow did not increase wheat yields. At Lind there were only slight increases in the yields from the summer fallow receiving immediate tillage as compared with delayed tillage. At Nephi more cultivation than that necessary to control weeds did not prove profitable on the average.

Studies of soil moisture and nitrate at Moro and Lind indicate that tillage practices have an important bearing on the accumulation of nitrate nitrogen in the soil. The quantity of nitrate nitrogen in the soil greatly influences the habit of growth of winter and spring wheats and the chemical composition of the wheat kernel.

Experiments to determine the effect on yield of harrowing winter wheat in the spring show that on the average this practice reduced yields at Moro, Lind, and Nephi.

In the date-of-seeding experiments with winter wheat at Moro in the years 1916 to 1928, inclusive, omitting 1925, slightly higher yields were obtained from sowing winter wheat from the middle to the end of September than at a later time. Yields of winter wheat were significantly decreased when it was sown as late as mid-November. The most profitable rate of sowing winter wheat at Moro was with the drill set to sow 5 pecks per acre of treated seed, or approximately 4 pecks per acre of dry seed. With spring wheat the highest yields were obtained at Moro from sowing early in the spring at the rate of 5 pecks per acre.

At Lind slightly higher yields were obtained from winter wheat sown early than from wheat sown midlate or late in the fall. No advantage, however, was found in sowing wheat in dry soil. Experiments to determine the best rate of sowing winter and spring wheats at Lind indicate that the most profitable rate for either is about 4 pecks per acre. Higher yields of spring wheat were obtained at Lind from early sowing.

In the experiments in rate and date of seeding at Nephi the results indicated that winter wheat should be sown at the rate of about 5 pecks to the acre between September 15 and October 1. Early seeding is advisable only when the soil contains sufficient moisture to insure a uniform and rapid germination.

In an experiment to determine the effect on yield of sowing winter wheat at different depths, no material difference was obtained at Moro during a 4-year period from wheat sown 2, 3½, and 5 inches deep. The depth of sowing winter wheat had an important influence on stand, especially when the wheat was sown late. At Lind there was an advantage from the shallow seeding of winter wheat. Sowing spring wheat at a depth of 4 inches gave slightly higher yields at Lind than sowing 1 and 2½ inches deep.

In a spacing experiment at Moro and Nephi the same quantity of winter wheat sown in rows 7 inches apart produced higher acre yields than when sown in rows 14 or more inches apart.

In experiments at Moro, Nephi, and Lind on the effect of the ordinary and furrow drills upon the yields of winter wheat, the results at all places slightly favored the use of the ordinary drill.

U. S. GOVERNMENT PRINTING OFFICE: 1932

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director Personnel and Business Administration	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Cereal Crops and Diseases	M. A. MCCALL, *Principal Agronomist, in Charge.*

Technical Bulletin No. 328 November, 1932

PEACH BROWN ROT

BY

JOHN W. ROBERTS
Senior Pathologist

AND

JOHN C. DUNEGAN
Associate Pathologist
Division of Horticultural Crops and Diseases
Bureau of Plant Industry

United States Department of Agriculture, Washington, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - Price 10 cents

TECHNICAL BULLETIN No. 328 NOVEMBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

PEACH BROWN ROT

By JOHN W. ROBERTS, *Senior Pathologist*, and JOHN C. DUNEGAN,[1] *Associate Pathologist, Division of Horticultural Crops and Diseases, Bureau of Plant Industry*

CONTENTS

	Page
Introduction	1
History of the disease in the United States	2
Losses caused by the disease	5
Varietal susceptibility	6
The fungus causing the disease	6
Taxonomic position	6
Geographic distribution	12
Morphology	12
Strains or physiologic forms	16
Homothallism	17
Growth on artificial media	18
Enzyme production	18
Function of vitamins in the metabolism of the fungus	19
Temperature relations	20
Relation of hydrogen-ion concentration to growth	20
Viability of spores	21
Germination of spores	22
Dissemination of the fungus	24
The fungus causing the disease—Continued.	
Host plants	25
Seasonal life history and pathogenicity of *Sclerotinia fructicola*	26
Survival in winter	26
Occurrence of apothecia	28
Discharge of ascospores	30
The blossom-blight phase of the disease	31
The fruit-rot and mummy phase of the disease	32
The canker and twig-blight phase of the disease	33
Leaf infection	38
Relation of insect pests to infection	38
Pathological anatomy	40
Control of peach brown rot	42
Sanitary measures	42
Spraying and dusting	44
Fumigation	48
Summary	51
Literature cited	54

INTRODUCTION

Brown rot is a destructive disease of the peach, *Prunus persica* Batsch,[2] and is caused by the fungus *Sclerotinia fructicola* (Wint.) Rehm. It is often called "peach rot" or "the rot" because, in the United States, with the occasional exception of Rhizopus rot, it is the only rot of the peach that is of great importance to producer, shipper, carrier, commission merchant, retailer, and consumer. All these at times suffer heavy financial losses because of brown rot. The disease is also the common rot of the cherry, plum, and other stone fruits. The apple, pear, and other pome fruits are sometimes attacked, but in the United States brown rot of these fruits is of slight importance. Peach brown rot is an important disease in all the peach-growing sections of the eastern part and particularly the southeastern part of the United States. It is of less importance in the Middle West but is often destructive in all peach orchards except those in arid or semiarid regions.

[1] The junior writer was transferred from Georgia to Arkansas in the fall of 1928, and the experiments in 1929 were made possible through the cooperation of W. F. Turner, at that time horticulturist for the Central of Georgia Railway. The writers wish to express their gratitude to Mr. Turner for his kindness in collecting and dispatching the cankers.

[2] Scientific names of host plants follow the usage of Rehder (*73*).[3] Common names follow Standardized Plant Names (*2*).

[3] Italic numbers in parentheses refer to Literature Cited, p. 54.

The first symptom of the disease on the fruit is the appearance of a tiny brown speck that rapidly develops into a large spot beneath which the flesh is deeply invaded. Soon the whole fruit may be involved if conditions of heat and moisture are favorable to rot development. The rotting of the tissue produced by the fungus is not of the soft watery type commonly caused by species of Penicillium and Rhizopus but is of the solid type similar to the black rot of apple caused by *Physalospora malorum* (Pk.) Shear.

Spore cushions or coremia appear on the surface of the rotted area, frequently within 24 hours after the initial appearance of the disease on the fruit. In a short time most of the surface of the spot is covered with ashen-gray masses of conidia, which are often, but not always, grouped in irregular concentric rings. The invaded fruit that remains attached to the tree slowly becomes dried and shriveled, forming what is usually called a mummy.

When the blossoms are attacked, they quickly turn brown and die. The blighted blossoms are not easily dislodged from the twig and frequently adhere throughout the season. They are covered with masses of conidia, which soon disappear if dry weather prevails; however, new crops of conidia may be produced throughout the season after each period of rainy weather.

The formation of twig cankers as the result of the fungus passing from the floral parts through the peduncles and into the tissues of the twigs is a frequent sequel to blossom blight. Twig cankers may also result from the passage of the fungus from infected fruits through the fruit stems and into the tissues of the twigs, but more often the twigs are killed. Twig cankers are easily recognized as brown, depressed spots at the bases of blighted blossoms or stems of infected fruits.

The leaves adjacent to, or in contact with, twig cankers, blighted blossoms, and rotted fruits are sometimes invaded by the fungus and become brown, but as a disease of peach foliage brown rot is of itself not important. The infected leaves have a water-soaked appearance and are frequently covered with conidial masses. The fungus may occur also on leaves that have been injured by other agencies, particularly the leaf-curl fungus, *Exoascus deformans* (Berk.) Fckl.

HISTORY OF THE DISEASE IN THE UNITED STATES

Most writers on brown rot credit Peck (*64*) with being the first to describe the disease as it occurs in the United States and the first to call attention to its economic importance. Humphrey (*46, p. 85*) states: "* * * the chief handbooks of plant diseases pass it with very brief mention or with none. * * * Here it was first described by Peck, in 1881, and by Arthur, in 1884." Quaintance (*70, p. 246*) makes a similar statement: "In the United States, the disease was first described in 1881 by Dr. C. H. Peck, and in 1884 by Dr. J. C. Arthur." Substantially the same statements are made by Scott and Ayres (*87*) and by Ezekiel (*34*).

Peck (*64*) was probably the first to give a good description of the rot and to demonstrate the pathogenicity of the fungus by means of inoculations. He also discussed the nomenclature of the fungus and included in his paper illustrations of the diseased fruit. Peck un-

doubtedly deserves all the credit that writers on the subject of brown rot have given him. It would be erroneous, however, to infer that brown rot had not been serious and had not been noted by various writers previous to 1880.

Tilton (*96, p. 194*), of Bellevue, near Wilmington, Del., in a letter to Richard Peters, of Philadelphia, dated November 6, 1807, and published in 1815, stated that "a little beetle, called curculio, about the size of a pea bug, is the insect which punctures the fruit, and occasions it to fall off or rot, before it comes to maturity." Evidently brown rot followed curculio in 1807, just as it does at the present time.

In 1817 Coxe (*23*) wrote the first American book on fruit growing. Although peach yellows and fire blight of pear are mentioned, nothing is said of the rot of peaches. However, in the unpublished manuscript for the second edition, which is dated May 30, 1829, and is in the library of the United States Department of Agriculture, the comment "not subject to rotting" follows a description of the peach variety, Morris's Large White Rareripe, on page 736.

In 1852 White (*99, p. 402*), of Athens, Ga., wrote:

> But our greatest obstacle in the culture of the plum is its tendency, in common with several varieties of the peach, nectarine, and grape, to rot before maturing. In a dry season, no matter how hot it may be, the fruit is not in much danger. But in a year like this, of warm, abundant, and continual rain, the cultivator may expect to lose, in the case of most varieties, from half to three-fourths of his crop, and of some it may be the whole will decay. He can guard against this only by selecting the varieties least affected.

Late in the same year he (*100, p. 556*) states:

> But in seasons like the present, the loss of peaches by decay while approaching maturity is more annoying than anything else in peach culture. When the season is warm and wet, very few kinds of peaches will ripen well, especially on moist or very rich soils.

Barry (*7, p. 355*), in his book on fruit growing, published in 1854, states:

> Peaches and other soft fruits should be pressed as lightly as possible, for anything like a squeeze is certainly followed by decay in the form of a brown spot, and this is the reason why it is exceedingly difficult to find a perfectly *sound* and at the same time *ripe* peach in our markets.

Kirtland (*49*) published an excellent description of plum brown rot in 1855 and stated he had known the disease for 30 years. He realized clearly that brown rot is a disease, as the following quotation shows:

> The plum crop, of late years, has generally failed in northern Ohio. The result has been charged to the curculio, and in many instances correctly; but a fatal disease has been insidiously progressing among our fruit orchards which has done more injury than that insect. The effect of the two evils has not usually been discriminated one from the other. Indeed few cultivators seem to be aware of the prevalence of any such disease.

Not only did Kirtland realize that brown rot was a definite disease, but he recognized its fungus origin and made an effort to identify the fungus. In Warder's book on American Pomology (*98, p. 182–183*), published in 1867, the following is quoted from an address by Doctor Kirtland before the Ohio Pomological Society:

> I have watched carefully the sudden and premature decay of our plum crop, at the period of its ripening, for the last fifteen years. From hints offered by the work of Prof. Mitchell, and several microscopic observations of my

own, I was induced to publish an article in "The Florist," of Philadelphia, in the year 1855, in which I imputed the origin of the disease to the Torula or some analogous species of parasite fungi. The disease still prevails among us, and it is sure to destroy all the plums which escape puncture by the curculio. It is, however, generally overlooked by pomologists, and its effects are charged to the depredations of that insect. Similar disease occasionally impairs our peach and apple crops, to a less extent. Whenever it occurs on either of these varieties of fruit, the spurs and young wood blight or canker, and cease to be fruitful for several years.

The blight of peach here mentioned was probably that caused by the brown-rot fungus, but the blight of the apple was more likely that caused by *Bacillus amylovorus* (Burr.) Trev.

Riley (*75, p. 52–53*), in 1869 in a discussion of the curculio, states:

* * * By its punctures it causes the dreaded peach-rot to spread, whenever that disease is prevalent, though it cannot possibly be the first cause of the disease. The peach-rot is now pretty generally acknowledged to be a contagious disease, of a fungoid nature, and I believe that the spores of this fungus, "a million of which might be put upon the point of a stick whittled down to nothing," attach themselves more readily to fruit which has the skin abraded, and from which the gum issues, than to whole or unpunctured fruit. With this belief I made some effort to procure, for the benefit of my readers, a synopsis of the growth of this fungus, but, alas! I find that nothing but confusion exists with regard to it. Upon applying to my friend, Dr. T. C. Hilgard, of St. Louis, a recognized authority on such subjects, he furnished me with the article which may be found in the *Journal of Agriculture* of January 16th, 1869. I most respectfully declined publishing it in these pages knowing that the reader would not be likely to understand what was either too *profound* or too befogged for my own comprehension, and those who require a *synopsis* of this fungus, are referred to that article. Verily we must conclude that Peach-rot is not yet much understood, if a more clear exposition of it cannot be given.[4]

Until quite recent times brown rot was accepted by most people as a thing inherent in the peach and bound to appear in moist weather as the peach reaches maturity, or as caused by the curculio. The fungus, when noticed, was apparently accepted as a natural and normal growth following the rot rather than causing it. A careful examination of Downing's (*30*) book (edition of 1876) on fruit growing fails to disclose a reference to peach brown rot, although the curculio, borer, and yellows are given much attention. Even so late as 1889 Smith (*91, p. 124*) stated:

The peach is well known to be a delicate and perishable fruit, but it is not so generally known through just what agencies this decay occurs. * * * Fruit growers, as a rule, are entirely ignorant of the presence of any fungus. They do not know the cause of the rot, but are painfully conscious of the result, since the latter can be expressed in pecuniary terms. The rot is frequently known as "scald" and is usually ascribed to hot and wet weather * * *.

In 1898 Selby (*89, p. 218*) wrote:

The belief that peaches rot solely because of the weather is often expressed; but while, to be sure, the weather influences the amount of rot, it is only a condition and not the cause of peach rot.

Brown rot of the peach, therefore, appears to have been an important disease for at least a hundred years; but although its true nature was suspected by a few, it was not generally regarded as a definite disease until after 1880.

---

[4] In the Journal of Agriculture of Jan. 30, 1869, there is a letter from Hilgard protesting that his paper had been "so utterly and illegibly defaced * * * by grievous errata." Despite ridiculous typographical errors, the paper shows that Hilgard had considerable knowledge of the fungus.

LOSSES CAUSED BY THE DISEASE

In the humid sections of the Eastern and especially the Southeastern States, brown rot is a menace to the peach crop nearly every year. Often it is the principal topic of conversation as peaches begin to ripen, for the orchardist well knows that at this time moist weather may favor the development of brown rot to such a degree that the crop which he has nurtured so carefully for many months may be destroyed as it reaches maturity.

Were it not for the control methods in common use, many sections in moist years would suffer an almost total loss. In seasons of high rainfall the writers frequently have seen the entire crop of individual orchards destroyed by the disease and the crop of whole sections reduced by as much as 75 per cent. In such years a large percentage of the remaining fruits, which are soft and watery and covered with conidia of the brown-rot fungus washed down on them from the infected fruits, may rot soon after picking. In regions of little rainfall peach brown rot is not present or, if present, is not important.

Smith (*91*) estimated the loss to peach growers of the Delaware-Chesapeake Peninsula in 1888 as $400,000. Quaintance (*70*) considered the loss to Georgia growers in 1900 as somewhere between $500,000 and $700,000. For the whole of the United States, Scott and Ayres (*87*) in 1910 estimated the annual losses caused by brown rot to be at least $5,000,000. They estimated that with a fair crop and average brown-rot conditions the loss to Georgia growers alone was $1,000,000 annually.

Orton (*62, p. 583*) in 1904 reported:

> Brown rot (*Sclerotinia fructigena*) varied in severity according to the weather in different sections. The main peach crop of middle Georgia was nearly free from rot. There was much greater loss in north Georgia, amounting to 15 per cent of the crop. In Maryland plums suffered most, the loss on varieties like Wickson and Abundance being 30 to 100 per cent, while early peaches were a complete loss and midseason varieties rotted badly. In the Northern States the disease occurred about as usual where the crop had not been destroyed by winter injury. There was little in Michigan.

In 1905 Orton (*63, p. 604*) further reported:

> Brown rot * * * was on the whole more destructive than usual. In Georgia the loss was greater in the southern than in the middle and northern peach sections of that State, and amounted to one-third of the crop, or 800 carloads. Maryland, New Jersey, and Connecticut suffered severely. In one instance in Pennsylvania 20 carloads were lost. The estimated damage in Ohio was $250,000. There was serious injury to the crop in West Virginia.

Two decades later the plant disease survey of the Bureau of Plant Industry, United States Department of Agriculture,[5] reported that in 1924 brown rot reduced the yield of peaches in the United States by 2,392,000 bushels, and in 1925 by 692,000 bushels. The average annual reduction for the years 1917 to 1925, inclusive, approximated 3,200,000 bushels. In 1926 the reduction in yield was estimated at 3 per cent, or 1,868,000 bushels; in 1927, it was 5 per cent, or 2,379,000 bushels.

---

[5] UNITED STATES DEPARTMENT OF AGRICULTURE, BUREAU OF PLANT INDUSTRY. CROP LOSSES FROM PLANT DISEASES * * * Plant Disease Bul. Sup. 6 (1919), 12 (1920), 18 (1921), 24 (1922). Plant Disease Rptr., Sup. 30 (1923), 36 (1924), 43 (1925), 49 (1926), 56 (1927), 64 (1928). [Mimeographed.]

These estimates, however, do not include the losses due to rot after the peaches have left the hands of the grower. Each year losses in transit and on the market are large, and frequently enormous. Peaches from sections where brown rot is prevalent, when shipped long distances, even in refrigerator cars, are sure to suffer from rot to some extent, especially in years of heavy rainfall, when peaches contain a high percentage of water and conidia of the fungus are invariably present. Frequently the loss is 25 per cent or more. Then in commission houses, stores, on fruit stands, and finally in the hands of the consumer, brown rot takes further toll. Beginning about 1908, the losses both in the orchard and in the market have been greatly reduced by the application of sprays to the developing fruits.

It is probable that most estimates do not include losses from the blossom-blight phase of the disease, which occasionally may prevent the setting of a full crop. The writers have seen cases in which 95 per cent of the blossoms of individual orchards have been killed by this phase of the disease.

VARIETAL SUSCEPTIBILITY

The modern commercial varieties of the peach show considerable resistance to brown rot in normal years. One of the reasons why they have supplanted the older and often better-flavored varieties is that they are less susceptible to brown rot in the orchard, in transit, in the market, and in the home.

Because of differences in time of ripening it is impossible to classify varieties according to their relative susceptibility to the rot phase of the disease, since in the same season the conditions at the time of ripening of one variety may be favorable to the development of rot, and at that of another variety unfavorable. Varieties that are normally resistant may in seasons of excessive rainfall produce fruit which, in place of having the usual firmness, is so soft and watery that it is very susceptible. Frequently the percentage of fruits punctured by the curculio determines the percentage of fruits affected with brown rot, regardless of the variety.

Practically all modern commercial varieties are more resistant to the blossom-blight phase of the disease than are the older ones, but all may be quite susceptible under optimum conditions for infection.

THE FUNGUS CAUSING THE DISEASE

TAXONOMIC POSITION

A discussion of the taxonomic position of the fungus causing the brown-rot disease of peaches in North America should start with the classification of similar fungi in Europe, because early American workers were in close contact with European mycologists, used the European systems of classification, and in a number of cases submitted their American specimens to European workers for identification. Reliance on European mycologists was logical and would have eliminated the confusion that now exists if, as was thought until recently, the American organism had been identical with a previously known European organism.

In 1796 Persoon (*65*) described a fungus causing a rot of fruit in Europe under the name of *Torula fructigena*. In 1801 he (*66*) decided that it belonged to the genus Monilia and renamed it *Monilia fructigena*. Kunze and Schmidt (*50*) considered that it should be called *Oidium fructigenum*. After considerable discussion by various writers, *M. fructigena* became the generally accepted name, although *O. fructigenum* was also used.

American mycologists early in the nineteenth century knew that a fungus was associated with the rot of peaches but apparently were not interested in considering whether it caused the disease or not. In fact, one infers that they assumed it to be a saprophyte developing in the rotted fruit.

De Schweinitz (*85, p. 128*), in his Synopsis Fungorum Carolinae Superioris, supposed to have been published in 1822, reports as item No. 130 "Torula fructigena. In Persicis frequens."

In Michener's collections,[6] volume 23, sheet 32, there is a specimen labeled "*Oidium fructigenum* Per. in fruct. Pruni. S. Car. dedet Ravenel." Also on sheet 34, "*Oidium fructigenum* Per. in fruct. putrescent. Pruni. S. Car. H. W. R."

The influence of the European workers is clearly shown in the names ascribed to the fungi collected by these early American investigators, and even as late as 1913 the American fungus was considered to be identical with *Monilia fructigena*.

In 1851 Bonorden (*13*) described another species occurring on fruits in Europe and named it *Monilia cinerea*. Although it had been accepted by Saccardo (*83, v. 4, p. 34*) and by Schröter (*84*), little attention was paid to this name until 1900, when Woronin (*111*) showed that the *M. fructigena* of Persoon and the *M. cinerea* of Bonorden were distinct species.

Eugene Rau, of Bethlehem, Pa., found in May, 1883, in a garden a decayed peach on which was growing the apothecia of a fungus. He kept part of this material with his own collection and sent a part to Winter (*104*), who described the fungus as a new species which he named *Ciboria fructicola*. Saccardo (*83, v. 18, p. 41*) accepted Winter's new species and copied Winter's description in the Sylloge Fungorum but placed it in the genus Sclerotinia on the authority of Rehm. The name appears in the Sylloge Fungorum as *Sclerotinia fructicola* (Wint.) Rehm.

In 1888, five years after Rau's discovery, Woronin (*110*) demonstrated the connection between a Monilia and a Sclerotinia growing on *Vaccinium vitis-idaea*. This discovery led Schröter (*84*) in 1893 to propose that *Monilia fructigena* and *M. cinerea* be placed in the genus Sclerotinia with the names *Sclerotinia fructigena* and *S. cinerea*, respectively. This is apparently the first time that these two fruit-rotting fungi were placed in the genus Sclerotinia, and it must be pointed out that Schröter had no grounds for his assumption other than analogy with the fungus on Vaccinium. He either overlooked Winter's description of *Ciboria fructicola* or failed to attach any significance to it.

The next development came in 1902 with the finding by Norton of apothecia of a species of Sclerotinia developing from peach mum-

[6] The Ezra Michener collection of fungi, in the herbarium of the Division of Mycology and Disease Survey, Bureau of Plant Industry, U. S. Department of Agriculture.

mies. By cultural work he demonstrated beyond any doubt their connection with the common Monilia causing a rot of fruits. Since this Monilia was generally believed to be identical with *M. fructigena* of Europe, Norton (*59*) named the fungus *Sclerotinia fructigena* (Pers.) Norton.

In 1905 Aderhold and Ruhland (*1*) reported the discovery of a Sclerotinia which they demonstrated to be the ascogenous stage of *Monilia fructigena.* They also declared the American fungus to be *Sclerotinia cinerea*, since the Monilia form of the American fungus and *M. cinerea* of Europe are so nearly alike. Their description of *S. cinerea* is based on preserved apothecia from the United States and on conidial material collected in Europe.

In the United States the work of Aderhold and Ruhland was not generally accepted, and *Sclerotinia fructigena* was commonly used as the name of the peach-rot fungus until about 1913, when Matheny (*56*) after studying fresh material from Europe and North America showed conclusively that the fungus was quite different from *S. fructigena* but resembled *S. cinerea* very closely. Matheny's conclusions have been verified by Conel (*18*), Bartram (*9*), Jehle (*48*) and others who have examined material or grown the fungi in culture. *S. cinerea* was generally accepted as the correct name for the common American fungus, and its identity with the European form was not questioned until about 1920.

In 1919 and 1920 Wormald (*105*) distinguished a number of different forms of *Sclerotinia cinerea.* Cultures of the American form fruited more readily on artificial media than did the strains occurring in England. Other differences between the Monilia forms were noted, including differences in enzyme production, in manner of growth on artificial media, and in length of germ tubes before branching. Wormald regarded the American form as distinct and referred to it as *Monilia cinerea* forma *americana.*

In 1921 Wormald (*106*) announced the discovery of a species of Sclerotinia which he showed to be the perfect stage of *Monilia cinerea.* He accepted the name *Sclerotinia cinerea* (Bon.) Schröter for the fungus, the ascogenous stage of which Schröter had never seen.

In 1923, at the December meeting of the American Phytopathological Society, Norton and Ezekiel (*61*) proposed the name *Sclerotinia americana* (Wormald) comb. nov. for the American form. They stated:

> The species mentioned can be differentiated macroscopically on potato-glucose agar plates by variation in the rate of growth, production of conidia and aerial hyphae, and shape and elevation of the colony.

At the time Rau made his discovery of apothecia arising from decayed peaches no connection between Monilia and Sclerotinia had been recognized or even postulated, so European and American investigators gave no particular attention to his discovery. It was not until 1909, 21 years after Woronin's discovery of the connection between Monilia and Sclerotinia, 16 years after Schröter's assumption that sclerotinial stages of *Monilia fructigena* and *M. cinerea* existed, and 7 years after Norton's demonstration of the sclerotinial stage of the common American fungus, that attention was called to the fungus collected by Rau and described by Winter. In that year

Pollock (*67*, *p. 53*) pointed out that since Winter's measurements of asci and ascospores agreed very closely with those given by Reade for the ascogenous stage of the American fungus, Winter must have had that species. He stated:

> If the rule of priority is to apply to the species name first associated with the perfect stage, the correct name of this fungus is Sclerotinia fructicola (Winter) Rehm instead of Sclerotinia fructigena (Pers.) Norton.

In 1920 Pollock[7] again called attention to *Sclerotinia fructicola*, which seemed to him to be the correct name of the common American brown-rot fungus, particularly since he now considered the American fungus distinct from European forms.

The writers (*77*) in 1924 reported that they had examined and made measurements of cotype specimens of *Sclerotinia fructicola* found in Rau's collections. They showed that the fungus collected by Rau and described by Winter was morphologically identical with the species of Sclerotinia commonly found on decayed peaches at the present time. They stated that if the American form is considered as a distinct species it should be called *Sclerotinia fructicola*, since that name had priority over *S. americana*. At that time, however, since the writers were not convinced that the American form was sufficiently distinct from the European to warrant specific rank, they preferred the name *S. cinerea*.

Ezekiel (*34*) in 1924 confirmed and enlarged upon Wormald's work. He showed that the American form and *Sclerotinia cinerea* forma *pruni* differ as to germ tubes, oxidase production, length of hyphal cells, rates of growth on artificial media and in inoculated fruits, and in the manner of growth on artificial media. Many of these differences had been noted by the writers but were not considered sufficient to constitute a distinct species, since the American form itself showed considerable physiologic variation.

Jackson (*47*) and Posey (*69*) as early as 1915 and Barss (*8*) in 1923 called attention to a Monilia attacking fruits on the Pacific coast which they reported as different from the common one found there. Barss (*8*) proposed for it the name *Monilia oregonensis* Barss and Posey. Ezekiel (*35*) in 1925 considered this fungus to be identical with *M. cinerea* forma *pruni* of Europe. He grew the different forms in culture and showed the close resemblance in physiologic behavior between *M. cinerea* of Europe and the Pacific coast form. The writers in 1927 (*79*) confirmed Ezekiel's results. Wormald (*107*) also confirmed them, affirming the Pacific coast fungus to be identical in culture with *M. cinerea* forma *pruni*. Since the typical American form and the fungus occurring on the Pacific coast can be distinguished in nature and in herbarium specimens as well as in artificial culture, the writers have receded from their former position and consider the common American form a distinct species, but they maintain that, since they have shown its identity with a fungus first described as *Ciboria fructicola*, the name *Sclerotinia fructicola* should be accepted as correct. Ezekiel (*35*) still prefers the name *S. americana* because there is, at present, no way of dis-

[7] POLLOCK, J. B. IDENTITY AND THE NAME OF THE SCLEROTINIA CAUSING THE BROWN ROT OF STONE FRUITS IN THE UNITED STATES. Paper read before the mycological section of the Botanical Society of America, Chicago, Dec. 30, 1920. (Unpublished.) Information also given in a letter to the senior writer.

tinguishing the apothecial stage of the common American fungus from that of *S. cinerea*. Wormald (*108*) has accepted *S. americana*, believing that the earlier name may have applied equally well to apothecia of *S. cinerea*. Wormald (*109*) takes this stand while pointing out that *S. cinerea* has been found only in the Pacific coast section of the United States, which is more than 2,000 miles from Pennsylvania and is about two-thirds as far from that State as the latter is from England. It should also be pointed out that the apothecial (Sclerotinia) stage of *S. cinerea* has never been found in the United States and that failure to find it has thrown some slight doubt on the accuracy of the determination of the Pacific coast fungus as *S. cinerea*. If these statements are correct, then it seems inconsistent to accept *S. cinerea* for the Pacific coast fungus, and to reject *S. fructicola* in favor of *S. americana* for the common brown-rot fungus.

Furthermore, it seems illogical to reject the name *S. fructicola* as Ezekiel and Wormald have done on the ground that the technical description does not distinguish between *S. fructicola* and *S. cinerea*. When *S. fructicola* was described in 1883, there was no description of the apothecial characters of *S. cinerea*. The apothecia of the latter were not found until 1921 (38 years later).[8] It seems to the writers that unless the apothecial characters of *S. cinerea* can be shown to be different from those of *S. fructicola* the question is really centered about the validity of the name *S. cinerea* and not about *S. fructicola*.

Many American investigators accept *Sclerotinia fructicola* as the correct name for the fungus, and Harrison (*40, p. 113–114*), an Australian investigator, states:

> The first valid name applied to the apothecial stage of the American Brown Rot fungus should be universally adopted when describing that fungus. Throughout this paper, therefore, the name *S. fructicola* (Wint.) Rehm will be used in preference to *S. americana* (Worm.) Norton and Ezekiel.

Honey (*44*) has recently chosen *Sclerotinia fructicola* as the type of a new genus, Monilinia, which is to include those forms formerly included in Sclerotinia that have a conidial stage belonging to the imperfect genus Monilia. Acceptance of this classification would give the brown-rot fungus the name *Monilinia fructicola* (Wint.) Honey. Hino (*43*), on the other hand, because of the existence of intermediate forms, thinks that the genus Sclerotinia should not be divided.

Granting that the common American fungus belongs to the genus Sclerotinia, then there are four names—*S. fructigena* (Pers.) Schröt., *S. cinerea* (Bon.) Schröt., *S. fructicola* (Wint.) Rehm, and *S. americana* (Wormald) Norton and Ezekiel—that must be considered before deciding on a name. Of these, *S. fructigena* has been shown by Woronin (*110*), Aderhold and Ruhland (*1*), Wormald (*105*), and others to be a name applied to a European fungus which Pollock (*67*), Matheny (*56*), Conel (*18*), Bartram (*9*), Jehle (*48*), and Wormald (*105*) have demonstrated is quite different from any known

[8] If *Sclerotinia cinerea* is considered identical with *S. laxa*, the year would be 1904 and the interval 21 years (Aderhold and Ruhland, *1*). T. H. Harrison, of the Hawkesbury Agricultural College, Richmond, New South Wales, Australia, in March, 1932, showed the writers an unpublished manuscript in which the identity of *S. laxa* and *S. cinerea* and the priority of the name *S. laxa* are demonstrated.

American species. The principal differences noted by them are as follows:

The conidial tufts do not agree in size, shape, or color. Those of *Sclerotinia fructigena* are yellow or buff in color and often grow together to form a smooth upper surface. Those of the common American form are ashen gray in color, much smaller, and do not coalesce.

The conidia of *S. fructigena* are regularly and consistently larger than those of the common American fungus. The former are short lived, the latter relatively long lived.

Although measurements of the asci and ascospores of both forms correspond very closely, the ascospores of *S. fructigena* are sharply pointed at each end and are free from oil droplets, whereas those of the American form are rounded at the end and possess oil droplets.

The American fungus usually rots fruits much more rapidly than does *S. fructigena.*

In artificial culture *S. fructigena* and the common American fungus behave quite differently.

The writers have grown *Sclerotinia fructigena* in artificial culture and have performed inoculation experiments with it. They also have examined fruits naturally infected by this fungus. They are in complete agreement with the foregoing statements. It should be added that the conidial tufts of *S. fructigena* are mainly composed of mycelium rather than conidia, whereas those of the American form are mainly composed of conidia. The conidial chains of the latter are much more easily broken up than are those of the former. All who have investigated the subject are agreed that *S. fructigena* is a species quite distinct from any form known to occur in North America.

After it had been shown so conclusively that *S. fructigena* of Europe is not identical with the common American form, *S. cinerea* became the commonly accepted name for the latter, because the conidial measurements were approximately the same and because *S. cinerea* was supposed to be serious as a disease of stone fruits only. Comparative studies of the Monilia stages of *S. cinerea* from Europe and of the American fungus, made by Pollock (*67*), Wormald (*105*), Norton and Ezekiel (*61*), and Roberts and Dunegan (*77*), revealed certain differences between the two organisms; and when Jackson (*47*), Posey (*69*), Barss (*8*), and Rudolph (*82*) concluded that another brown-rot fungus exists in the United States, the Monilia stage of which Ezekiel (*35*) has shown to be similar to, and probably identical with, that of the true *S. cinerea* of Europe, it became evident that the common form could no longer correctly be called *S. cinerea.*

The chief reasons for considering the common American form distinct from *S. cinerea* are as follows:

S. cinerea causes principally a destructive blossom, spur, and twig blight of both pome and stone fruits rather than a fruit rot primarily of stone fruits.

It forms on the blighted parts persistent conidia-producing mycelial cushions which are quite different from the evanescent tufts of conidial chains produced on diseased parts by the common form. From these cushions conidia are produced mainly in late winter or early spring of the year following infection. From twig cankers caused by the common form, tufts of conidia are produced soon after the blight begins to appear, and may continue to be produced on the cankers at intervals throughout the season, but are produced rarely in the late winter or early spring of the year following infection.

No apothecial stage of *S. cinerea* has been found in the United States, whereas the apothecial stage of the common form is abundant.

The common American form usually rots fruits much more rapidly than does *S. cinerea.*

The lengths of the conidial germ tubes before branching and the manner of branching are different in the two forms.

The common American form gives a much more powerful test for the presence of oxidases than does *S. cinerea*.

On culture media the common American form usually produces conidia more readily and grows more rapidly. The margin of its growth is usually even, whereas that of *S. cinerea* is usually scalloped or lobed.

Sclerotinia americana can not be accepted as a valid name because it is antedated by *S. fructicola*.

S. fructicola should be accepted as the correct name for the common American fungus because it was the first name to be applied to it. The proposal of the name was accompanied by an adequate description and complied with all the customary rules of nomenclature.

The reasons for considering the apothecia, collected in 1883, and described as *Ciboria fructicola* by Winter in the same year, identical with the apothecial stage of the common American fungus are as follows:

The apothecia collected in 1883 developed from sclerotia investing a decayed peach.

They were found in Pennsylvania, where brown rot is a serious disease, and in May, which in the latitude of Pennsylvania is within the season for the production of apothecia by the fungus.

The original collection has been examined and found to consist of dried apothecia and sclerotia. Measurements of apothecia, ascospores, asci, and paraphyses from this collection correspond closely with those of the common brown-rot fungus collected at the present time.

Apothecia of no other species of Sclerotinia which could be confused with those of the common brown-rot fungus are known to occur on fallen-peach mummies in Pennsylvania or elsewhere in the United States. The apothecial stage of the only other species of Monilia known to occur on peaches in the United States has never been collected in this country, even on the Pacific coast, which is the only section in which the fungus is known to occur.

GEOGRAPHIC DISTRIBUTION

The fungus *Sclerotinia fructicola*, causing the common brown rot of fruit in the United States, has also been reported from Canada, Australia, and New Zealand. Wormald (*107*, *108*) states that he received a culture from Holland which was indistinguishable from the common American form. It is doubtful, he thinks, whether the common American brown-rot fungus occurs naturally in Europe.

A fungus considered to be identical with *S. cinerea*, common in Europe, occurs on the Pacific coast of the United States and Canada along with the common form, but so far as known does not cause a serious fruit rot of the peach.

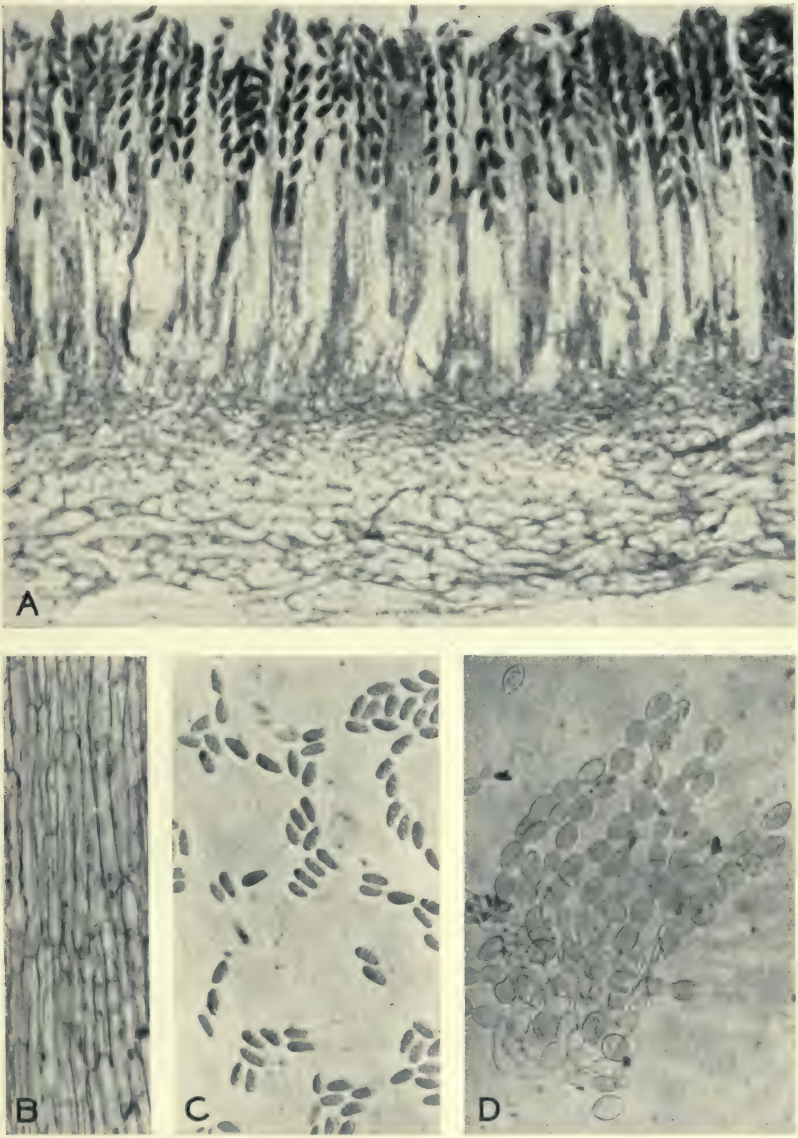
MORPHOLOGY

APOTHECIA

In 1902 Norton (*59*, *p. 93*) published an excellent account of the apothecia of the fungus. The following description is quoted from his paper:

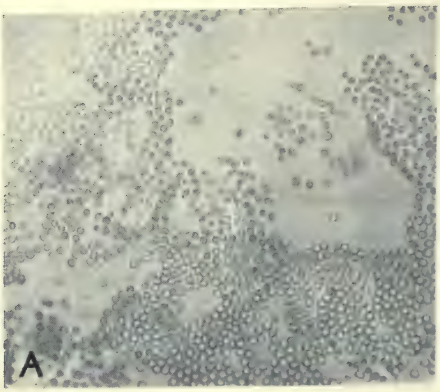
The apothecia arise from the familiar sclerotia in the tissues of the so-called mummy fruits beneath the soil or occasionally on the surface in moist places. Usually several arise from the under side of each fruit and appear in a ring around it at the surface of the ground, from 1 to 20 appearing above one fruit.

The sinuous stipe is from .5–3 cm. long, depending on the length it must grow to bring the spore-bearing surface above the ground. It is from .3–1.5



SCLEROTINIA FRUCTICOLA

A, Portion of the hymenium of an apothecium, showing mature asci and spores; B, portion of the stipe of an apothecium, showing the structure; C, ascospores; D, conidia. All × 340.



SCLEROTINIA FRUCTICOLA AND PEACH BROWN-ROT MUMMIES

A, Microconidia. × 340. B, Culture 77 days old on oatmeal agar, showing masses of microconidia collected on the surface as viscid droplets. × 1½. C, Germinating ascopores. × 340. D, Germinating conidia. × 340. E, Germinating conidia, showing anastomoses between parallel germ tubes. × 340. F, Brown-rot mummies, Uneeda variety, covered with fresh pustules of conidia. Collected December 21, 1923. Natural size.

mm. thick. The lower part is covered with closely adherent particles of soil entangled in a mass of slender dark-colored septate rhizoids 1 mm. or less in length. These gradually disappear upward, the upper part of the stipe being smooth. The color is dark brown below running into the lighter brown of the disk above. The body of the stipe is made up of somewhat elongated cells in the center with short dark-colored cells on the outside, composing the cortex which continues around the outside of the disk and projects at the edges somewhat beyond the hymenium. The subhymenium is composed of elongated intertwined cells much like those in the center of the stipe.

The stipe enlarges into the at first campanulate disk slightly broader below the top. The disk widens out until cup-shaped and finally flat. Older ones often have the edges torn and recurved. The disk becomes again campanulate in drying up and is then darker colored. The expanded disk is from 2–15 mm. wide, usually about 5–8 mm. In its later stages it is often whitish from a deposit of spores.

The structure of the hymenium and the stipe is illustrated in Plate 1, A and B.

ASCI

The asci (pl. 1, A) are cylindrical to club-shaped with rounded apices. They taper gradually in the lower half to the point of attachment. The pore, according to Reade (*72*) and Roberts and Dunegan (*77*), is stained blue with iodine, while Aderhold and Ruhland (*1*) state that it was not so stained in the material (apothecia preserved in spirits received from Norton) that they studied.

ASCOSPORES

The eight monostichous hyaline ascospores found in each ascus are ellipsoid to ovoid in shape with rounded ends. The monostichous arrangement becomes irregular just before the spores are discharged. The spores contain oil droplets and are nonseptate while in the ascus but may become 2-celled prior to germination. (Pl. 1, C, and Pl. 2, C.) Measurements of asci and ascospores by various investigators are summarized in Table 1.

TABLE 1.—*Summary of measurements of asci and ascospores of Sclerotinia fructicola*

Investigator	Date	Host	Asci	Ascospores	Remarks
			Microns	*Microns*	
Winter (*104*)	1883	Peach	130–160 by 8–8.5	10–12.5 by 4–5.5	Dried material from Rau.
Norton (*59*) [1]	1902	do	45–60 by 3–4	6–7 by 3–3.5	Fresh material.
Aderhold and Ruhland (*1*).	1905	do	89.3–107.6 by 5.9–6.8	6.2–9.3 by 3.1–4.6	Preserved material from Norton.
Reade (*72*)	1908	Stone fruits	125–215 by 7–10	10–15 by 5–8	Fresh material.
Pollock (*67*)	1909	Plum	130–179 by 9.2–11.5	11.4–14.4 by 5–7	Do.
Matheny (*56*)	1913	Peach	135–190 by 6.9–10.5	10.5–14.5 by 5.2–7.5	
Do	1913	Plum	137–173 by 6.8–10.8	9.3–14.2 by 5–7.4	
Valleau (*97*)	1914	do	102–166 by 3.5–5.7	5.6–8.9 by 2.9–3.8	Do.
Bartram (*9*)	1916	Stone fruits	150.4–8.8	10.1 by 7.1	
Jehle (*60*)	1912–1920	do	136–185 by 7.8–10	10–16 by 5.8	
Roberts (*77*)	1920	Peach	152–176 by 8–10	6–15 by 4–8	Do.
Norton (*60*)	1910–1923	Stone fruits	89–125–150	9.2–16.7 by 4.1–8.1	
Harrison (*40*)	1922	Plum	116–190 by 10	10.5–16.3 by 5.75–8.2	Fresh Australian material.
Do	1922	Peach	135.6 by 7.8		Preserved material from New Zealand.
Dunegan (*77*)	1922–1923.	do	130–186 by 5.7–13.3	9.5–14 by 5.7–7.6	Fresh material.
Do	1924	do	117–161 by 5.7–9.5	6.8–13.1 by 3.4–6.8	Rau's dried material.

[1] Norton, Ezekiel, and Jehle (*60, p. 12*) state: "The measurements by Norton (1902) are about one-half the usual sizes, apparently due to an error in computing the magnification."

PARAPHYSES

The paraphyses are filiform, hyaline, septate, with rounded, slightly swollen tips. In general they are unbranched, although branched ones are occasionally observed. They are approximately the same length as the asci and from 2 to 4 μ wide.

CONIDIA

Reade (*72*) appears to have been the first to give a complete description of the conidial stage. He apparently agreed with Humphrey (*46*) that the conidia should be considered as chlamydospores, following Brefeld's usage of the term for spores not produced in fructificative fashion on specialized spore-bearing threads. Reade's description (*72, p. 115*) is as follows:

> Chlamydospores [conidia] cespitulose, pulvinate, scattered or in concentric circles, minute to 2 mm usually 0.5 to 1 mm in diameter, at first cinereous, later on cherries and plums becoming ochraceous-buff to Isabella color (R.), on peaches ecru drab to Isabella color (R.), on pears and apples acquiring a blackish tinge, lemon-shaped, 10–28≷7–17 μ, mostly 17≷11 μ continuous, hyaline, in articulate, di- or trichotomously branched chains without disjunctors.

Matheny (*56*), Conel (*18*), and Bartram (*9*) describe the conidial tufts as "ashy" or "ashen-gray."

The writers have observed the conidial tufts on a large number of different hosts. They find the conidial tufts to be ashen gray when young, becoming darker to almost black with age. The tufts are easily rubbed off and are not formed from definite mycelial cushions as are those of *Sclerotinia cinerea* and *S. fructigena*. Measurements of conidia by various investigators reveal considerable variation in size. These measurements are summarized in Table 2. The formation of conidia in chains is illustrated in Plate 1, D.

TABLE 2.—*Summary of measurements of conidia of Sclerotinia fructicola*

Authority	Date	Host	Measurements of conidia
			Microns
Reade (*72*)	1908	Stone fruits	10–28 by 7–17.
Pollock (*67*)	1909	Plum	14.4–24 by 9.6–14.4.
Matheny (*56*)	1913	Peach and plum	14.4 by 10.8.
Conel (*18*)	1914	(?)	13.3 by 7.6.
Valleau (*97*)	1915	Plum	15.95–17.38 by 10.98–12.1.
Do (*97*)	1915	Apple	15.3–15.8 by 10.76–10.81.
Bartram (*9*)	1916	Plum	14.3–18 by 9–14.3.
Dunegan (*77*)	1922–1923	Peach	7.6–19 by 5.7–15.2.
Wormald (*107*)	1927	Peach, 3 sources	9–22 by 7.5–16. 10–18.5 by 8–11.5. 8–18 by 6.5–14.
Do (*107*)	1927	Plum	11–24.5 by 8.5–19.
Harrison (*40*)	1928	Peach	10.9–21.7 by 6.7–14.9.
Do	1928	Quince	11.5–19.2 by 9.6–13.4.

MICROCONIDIA

The microconidial phase was described by Humphrey (*46, p. 88*) as follows:

> * * * the mycelium of the fungus has given rise to immense numbers of closely-set flask-shaped sterigmata, reminding one of those of *Aspergillus*. Each of these produces at its outer or neck end small globular spores of about 3 μ in diameter, every one of which contains a conspicuous oil globule. One rarely finds more than one of these attached to the sterigma, but their vast number and the occasional observation of several still united shows that they must be produced in chains, like *Aspergillus* spores.

Reade (*72, p. 115*) states: "Microconidia formed in cultures on germinating spores, chlamydospores [conidia] and mycelium, spherical, hyaline, 2 to 4 μ, with a central refractive spot."

Pollock (*67, p. 52*) observes:

* * * mycelium from the ascospores also produces flask-shaped conidiophores with microconidia, globular bodies 2.5–3 micromillimeters in diameter. In some cases these flask-shaped conidiophores grow almost directly upon the ascospores or crowded on a very short germ tube. Dense tufts of these conidiophores bearing conidia are also found on the well-developed mycelium.

Valleau (*97, p. 374*) states:

The production of the microconidia was first seen by the writer in a potato-plug culture of the local fungus nearly a year old. The spores ranged from 2.2 to 2.6 μ in diameter, were spherical, and contained a large refractive globule. They were later found on agar cultures in great abundance, in hanging drops of distilled water, and also in hanging drops of 1 per cent malic, 0.062 gallic, 0.062 and 0.25 per cent tannic acids. In the latter cases the flask-shaped sterigmata could be seen. Chains of from 15 to 20 spores were not uncommon. They were also produced in great abundance on the surface of a very young Surprise plum picked and inoculated June 3. These spores ranged in size from 2.55 μ to 3.22 μ, averaging for 25 measurements 2.72 μ. The microconidia produced in the 1 per cent malic-acid solution were larger, ranging from 2.60 to 3.79 μ, measurements of 25 spores averaging 3.14 μ.

The writers have observed the production of microconidia on flask-shaped conidiophores that had developed from vegetative hyphae, on germ tubes produced by the germination of ascospores and conidia, and occasionally directly on ascospores, which apparently had been discharged and had fallen back on the surface of the apothecia. The microconidiophores were produced directly from the ascospore without the intervention of a germ tube.

The flask-shaped microconidiophores have an average length of about 6 μ and an average width of about 2 μ. They may occur singly or in compact masses which seem to be arranged in whorls. The microconidia, which are produced in chains at the tops of the conidiophores, are globose, uniformly 2 to 3 μ in diameter, with an oil drop. (Pl. 2, A.) In cultures microconidia are frequently produced in great abundance, and their masses are visible as viscid, cream-colored droplets on the surface of the medium. (Pl. 2, B.) They may be present in 3-day-old cultures, but they begin to appear in abundance after two weeks. They are usually much more abundant in dextrose-potato agar cultures than in potato agar cultures without dextrose. In old cultures the droplets may run together to form a whitish slime over the surface of the culture medium.

Hino (*43*) considers the microconidia of species of Sclerotinia to be degenerated abortive forms of normal macroconidia that have lost the power of germination and further growth. He claims that microconidia are a symbol of the genus Sclerotinia because they are to be found in all species under all conditions.

MYCELIUM

The mycelium has received slight attention from most investigators, with the exception of Ezekiel (*34*), who recognized hyphal characters as an aid in distinguishing *Sclerotinia fructicola* from *S. cinerea*. He described the hyphae as long, straight, and simply branched in artificial cultures. The mean length of hyphal cells as determined by many measurements was 66.2 μ.

SCLEROTIUM

The sclerotium is a dark-colored, tough, horny, more or less wrinkled structure which invests the mummied peach and from which apothecia, conidia, and microconidia may be produced. Norton, Ezekiel, and Jehle (*60, p. 6*) describe it as

> a dense layer of dark, thick, hyphae of the fungus mingled with or surrounding the partly preserved cells of the fruit. On the outside of the sclerotium the fungus threads are darker and thicker-walled, the inner layers lighter.

Honey (*44*) gives excellent reasons why this mixture of fungus and host tissues should be called a pseudosclerotium.

GERM TUBES

The characters of the conidial germ tubes are of value in distinguishing *Sclerotinia fructicola* from *S. cinerea*, as has been pointed out by Wormald (*105*) and by Ezekiel (*34*). *S. fructicola* has long straight germ tubes which do not branch until they have attained a length of at least 100 μ. (Pl. 2, D.) The germ tubes of *S. cinerea* are much shorter and are twisted and bent. Branching begins soon after the germ tubes are protruded.

OTHER STRUCTURES

Other structures have been noted by investigators from time to time, especially when the fungus is grown in artificial cultures. The thick-walled resting spores mentioned by Humphrey (*46*) and Quaintance (*70*) are often seen and are believed by the writers to be sclerotial in nature. The oblong bodies observed by Humphrey (*46*) budding from many points along certain hyphal threads have also been observed by the writers. They seem to be aborted conidial chains.

STRAINS OR PHYSIOLOGIC FORMS

Differences in the behavior of strains of the fungus obtained from different sources have been noted particularly by Ezekiel (*34*) and by Seal (*88*). The former has shown that strains of *Sclerotinia fructicola* vary in cultural characters, production of oxidase, and effects on inoculated fruits. He also believes that they show constant variations in the size of conidia, but to the writers the differences seem too slight to be significant. He also noticed variations in the shape of apothecia, to which, however, he did not give much consideration, since he did not know whether or not they were constant.

On the basis of differences in growth on potato-dextrose agar, Ezekiel (*34, p. 138*) distinguished 6 varieties into which the more than 30 strains that he studied could be grouped. The varieties are distinguished by their habit of growth on potato-dextrose agar at 25° C. in tube cultures, and at 15° in plate cultures, as follows:

Var. I. Tube culture: conidia and microconidia abundant, hyphae only trace, no hyphal masses. Cultures flat.
Plate culture: conidia very abundant in concentric circles, hyphae inconspicuous, no hyphal masses.

Var. II. Tube culture: both hyphae and conidia medium to abundant, hyphal masses rarely if ever present.
Plate culture: conidia abundant in concentric circles. Hyphae few but visible macroscopically.

Var. III. Tube culture: hyphae and conidia medium to abundant, hyphal masses present.
Plate culture: conidia abundant in concentric circles. Hyphal masses may be present.
Var. IV. Tube culture: conidia trace to few, only at the top of slant. Hyphal masses very abundant.
Plate culture: conidia abundant in concentric circles. Hyphal masses may be present.
Var. V. Tube culture: conidia very few, if present visible only microscopically and not as pustules. Hyphae abundant, not in hyphal masses.
Plate culture: conidia present in concentric circles in center of colony, hyphae more abundant toward the periphery.
Var. VI. Tube culture: conidia very few, if present visible only microscopically and not as pustules. Hyphae abundant, never in definite hyphal masses.
Plate culture: conidia as in tube cultures. Hyphae abundant, forming concentric circles. No hyphal masses.

Seal (*88*, *Table 1*, *p. 282*) distinguished at least two physiologic forms, which showed constant differences when grown on various substrata and under various environmental conditions. The two forms showed the following physiologic characters:

FORM 1

On fruits: Slow rot; necrotic area more or less confined to the surface area, not extending deeply into the fruit; fruiting pustules small, compact, and olive colored; * * * at first scanty, but after 10 to 15 days dense, compact * * * . The fruit blackens on decay.
On artificial media: Sparse production of aerial mycelium. Spores produced abundantly in small, ashy-gray tufts. On prune agar and in liquid cultures only little mycelium produced. Darkens the substrate to a dark brown or black. On prune agar spore production very scant.

FORM 2

On fruits: More rapid rot; necrotic area more or less confined to the surface, but extending deeper into the flesh of the fruit; fruiting pustules larger, less compact, scattered, and ash gray to olive in color. Fruiting pustules after 10 to 15 days not so compact, but mycelium more abundantly produced. The fruit turns brown on decay, not black.
On artificial media: Moderately heavy production of aerial mycelium. Spore production less abundant and in medium-sized ashy-gray tufts. On prune agar and in liquid cultures mycelial development more abundant. Darkens the substrate only slightly or not at all. On prune agar spore production more abundant.

The writers have noted that some strains when grown on 4 per cent potato agar grow much more rapidly than others. Some produce conidia abundantly, others very sparsely. Occasionally a form will be isolated which at first produces conidia sparsely and microconidia in great abundance; but after it is grown in culture for several years, the production of microconidia is greatly decreased. The writers isolated a strain of this type from an apple in 1924. Some strains when grown on beef agar darken the medium very rapidly; others require two weeks or more. On the other hand, one strain has been grown for 10 years, and two strains for 7 years continuously in tube cultures of potato hard agar, with and without dextrose, all of which have at different times shown the various combinations of characters that distinguish Ezekiel's varieties.

HOMOTHALLISM

According to Ezekiel (*34*), *Sclerotinia fructicola* is homothallic. He came to this conclusion because apothecia were developed from

peach fruits inoculated with strains arising from single ascospores, and because there was no apparent reaction, other than anastomoses, between strains grown near each other in the same Petri dish. Whether the fungus is homothallic or heterothallic would be extremely difficult to demonstrate conclusively, because no sexual organs are produced on artificial media and because one can not be sure that fruit inoculated with single ascospore cultures may not also become naturally inoculated with vagrant conidia commonly present on the surface of peaches and plums.

GROWTH ON ARTIFICIAL MEDIA

In general the fungus may be said to grow readily on a variety of artificial media. A much-favored medium is 4 per cent potato agar or potato-dextrose agar. On potato-dextrose agar conidia are frequently produced in two days, and the entire slant may be covered with conidial masses in three days. When the dextrose is omitted growth is slower, but conidial production is much more profuse and without the production of aerial hyphae.

Another medium, which the authors have used extensively, is potato plugs soaked in 7 per cent malic acid for 48 hours as recommended by Wiltshire (*103*). The fungus grows readily on the plugs, with profuse production of conidia and microconidia.

Most cultures of the fungus grow very rapidly and produce conidia and microconidia profusely on the potato agars and to a lesser extent on all the common media; some, however, grow more slowly with a comparatively scant production of conidia on the potato agars and with little or no conidial production on many of the common media. Some media, such as beef agar, are turned black by the growth of the fungus. On other media, such as corn-meal agar, the growth is almost invisible to the unaided eye except at points where conidia are produced.

As pointed out by Wormald (*105*) and Ezekiel (*34*), growth characters on artificial media are an aid in differentiating *S. fructicola* and *S. cinerea* forma *pruni*. In Petri dishes of potato agar the former grows very rapidly, producing conidia profusely, usually in concentric zones, whereas *S. cinerea* forma *pruni* grows much more slowly and produces few or no conidia. The margins of the colonies of *S. fructicola* are smooth, but those of *S. cinerea* forma *pruni* are deeply scalloped.

So far as known, the Sclerotinia stage has not been produced in artificial cultures except that Reade (*72, p. 115*) states that the fungus has been grown on artificial media from ascospores to ascospores again.

ENZYME PRODUCTION

By use of the guaiacum emulsion and pyrogallic acid tests Wormald (*106*) demonstrated the production of a much greater quantity of oxidase by *Sclerotinia fructicola* than by *S. cinerea*. By use of the guaiacum emulsion test Ezekiel (*34*) confirmed Wormald's results, but showed that the various strains of *S. fructicola* vary greatly in the readiness with which they produce oxidase.

Cooley (*20*) found that there was a very slight cytolytic action with respect to cellulose from the plum, but that cellulose from filter

paper was readily hydrolyzed when it was the only carbohydrate available.

In the discussion of enzymes involved in the changes of pectic substances the classification used by Atkins (*6*) and by Willaman (*101*) will be followed, i. e.:

Pectase.—Coagulates soluble pectin to a gel in the presence of traces of salts.
Pectinase.—Hydrolyzes soluble pectin and also the gel formed by pectase to sugars.
Pectosinase.—Dissolves the middle lamella to form soluble pectin.

Cooley (*20*) demonstrated the production of pectase by growing the organism in a solution of pectin obtained from plums. He was unable, however, to demonstrate that the fungus dissolved the middle lamella in tissues of infected fruits and was unable to observe any action by the fungus on calcium pectinate prepared from pectin obtained from plums. Therefore, there appeared to be no production of pectosinase.

Valleau (*97*) noted that the middle lamella is dissolved slightly in advance of the penetration of the hyphae but was unable to demonstrate the presence of pectosinase in rotting fruits or to extract it from a culture of the fungus on apple cider.

Willaman (*101*) demonstrated the production of pectase and showed that the middle lamella was probably changed to soluble pectin by the action of pectosinase. The production of pectinase was postulated but not demonstrated.

Muhleman (*58*) prepared an active pectosinase[9] solution by drying and grinding in silica the feltlike growth of mycelium produced on prune juice. He found that a growth of 3 to 5 days gave the most active pectosinase but that the color of the felts and of the ground material and not the age of the crop in days or hours should govern one's conclusions as to its activities. In the more active preparations the color of the ground mass was light chocolate. With active pectosinase preparations disks of green plums, green apples, green peaches, and ripe tomatoes 0.5 mm thick were macerated in 1.5 to 4 hours.

Hawkins (*41*), as a result of studies on the effects of the brown-rot fungus on the composition of the peach, found that the pentosan content remains the same, the acid content is increased, total sugar is decreased, and sucrose is changed to invert sugar. He also found that the amount of alcohol-insoluble substances that reduce Fehling's solution when hydrolyzed with dilute hydrochloric acid decreases.

Davidson and Willaman (*28*) prepared pectase and pectinase, but not protopectinase, from mycelium of *Sclerotinia fructicola.*

FUNCTION OF VITAMINS IN THE METABOLISM OF THE FUNGUS

Willaman (*102*) found that the fungus would not grow in a medium composed of sucrose, various salts, and asparagine. When small amounts of plant decoctions, especially those from peaches and plums, were added to the medium, growth was induced. His experiments indicated that the factor supplied by the plant decoction was of the nature of a vitamin.

[9] In Muhleman's paper the preparation is termed an "active pectinase solution." Since the preparation attacked the middle lamella in fruit disks, the writers are calling it pectosinase in accord with the classification of Atkins and Willaman.

There was some evidence from his experiments that two separate vitamin factors, one for vegetative growth and one for reproduction, are involved in the life history of the fungus. However, most of the experimental evidence he obtained indicated that the existence of but a single vitamin for the fungus is the more plausible hypothesis. No definite conclusions were reached concerning the identity of the vitamin involved, but he thought it might possibly be identical with water-soluble vitamin B.

TEMPERATURE RELATIONS

Many peach growers think that the higher temperatures of summer are more favorable to the development of brown rot than are the average or lower temperatures. They do not consider that when the maximum for the day is in the 90's the temperature may be between 75° and 80° F. during a large part of the 24 hours. This is the optimum temperature range for the growth of the fungus, whereas temperatures over 90° are distinctly unfavorable to its growth. The writers have had cultures on potato agar die in summer under the high temperatures (90° to 100°) prevailing in their laboratories. Sometimes for several days the temperatures would not fall below 90° even at night, when the closed laboratories prevented the entrance of the cooler night air.

Ames (*3*) showed that the fungus would germinate at 0° C., but that growth was very slow. The optimum temperature for growth was 25°, and the thermal death point was about 53°. Conidia (plum strain) did not germinate at 36°, and after 36 hours at 37° did not germinate when removed to an optimum temperature. Conidia (peach strain) did not germinate above 30°.

In experiments by Brooks and Cooley (*14*) the fungus produced measurable apple rots at 5° C. in one week and at 0° C. in two weeks. It also grew on corn-meal agar at 0°, making a measurable growth at the end of the second day. Both on fruit and on artificial media the optimum for growth was 25°, with some growth at 30°. In further experiments the same authors (*15*) found that the fungus produced measurable rots on peaches at 10° in 3 days, at 5° in 6 days, and at 2.5° in 12 days. "Low temperatures," they stated (*15, p. 465*), "have resulted in relatively less inhibition of the growth with Monilia when grown on peaches than when grown on potato-dextrose agar." Ezekiel (*34*) detected no consistent differences in the cardinal temperatures of various strains, the minimum, optimum, and maximum falling near 3°, 25°, and 33°, respectively, for all.

RELATION OF HYDROGEN-ION CONCENTRATION TO GROWTH

Cooley (*20*) grew the fungus in a series of flasks each of which contained sterilized cherry juice of different but known acidity. He found that although the fungus would grow on a medium as acid as the natural juice of sour cherries, it grew more luxuriantly on a somewhat less acid medium. On nearly neutral media there was at first no perceptible growth, but at the end of two weeks there was nearly as much growth as on the acid media.

Ezekiel (*33*) and Norton, Ezekiel, and Jehle (*60*) made a special study of the effect of hydrogen-ion concentration on the production of apothecia. By partly immersing sclerotia in fluids of various pH

values and at the same time maintaining other conditions favorable for apothecial production, they found that the optimum hydrogen-ion concentration for the growth of apothecia appeared to be near pH 2.5. Apothecia at this concentration developed more rapidly and more abundantly than at any of the others. In one series, for example, apothecia at pH 2.5 were mature and expelled their ascospores two days earlier than those at pH 3.8, and these in turn matured much more rapidly than the checks, the sclerotia of which were partly immersed in distilled water. With one exception the limits of growth were pH 1.4 and 6.8, and even at these points the apothecia did not mature normally.

Dunn (*31*) grew the fungus in sterilized peach solutions adjusted to different pH values by the use of a number of acids. With sulphuric acid the greatest growth was obtained at pH 2.84, with phosphoric acid at pH 3.90, and with formic acid at pH 4.37. In one series with acetic acid growth was 109 per cent of that of the control at pH 4.66, while in another series there was no increase over the control. With butyric and salicylic acids, an increase in active acidity caused no increase in growth over the control for the series. With increasing hydrogen-ion concentration the pH values of the first cultures that showed no growth depended on the acids used. Thus, for sulphuric acid the pH value was 1.85, for phosphoric acid 2.20, for formic acid 3.87, for acetic acid 4.45, for butyric acid 4.5, and for salicylic acid slightly above 4.64. The values for the fatty acids were dependent on the initial acidity of the culture solution. As the acidity increased, the amount of mycelium decreased, and usually there was a marked increase in conidial production until the higher limits of acidity were reached.

VIABILITY OF SPORES

ASCOSPORES

On March 28, 1921, mature apothecia were placed hymenium downward in clean dry shell vials, one apothecium to a vial, so that the ascospores were discharged against the bottom and walls of the vials. Two days later the dried apothecia were removed. At intervals a small amount of sterile water was poured into one of the vials, the walls and bottom scraped, and the water stirred with a glass rod. The entire amount of water with suspended ascospores was used in pouring five plates of potato agar. The results are presented in Table 3. These results indicate that, if kept dry, ascospores may remain viable for five weeks, but that the percentage of viability decreases rapidly from the time of maturity.

TABLE 3.—*Longevity of ascospores of Sclerotinia fructicola*

Date	Time after collection of apothecia	Colonies of S. fructicola present in poured plates	Date	Time after collection of apothecia	Colonies of S. fructicola present in poured plates
	Days			*Days*	
Mar. 30	3	191	Apr. 26	29	0
Apr. 5	8	66	May 2	35	12
Apr. 11	14	6	June 3	67	0
Apr. 18	21	1	June 8	72	0

CONIDIA

Conidia produced naturally in the orchard are often long lived and able to survive subzero temperatures. Arthur (*5*) in 1886 germinated conidia from cherry mummies that had hung on a tree all winter. Galloway (*39*) in 1889 reported that in May, 1888, he had germinated conidia from mummies collected in July, 1886. Smith (*92*) in 1891 was able to germinate conidia from dry material 1 year old. Chester (*17*) in 1893 noted that conidia on mummies collected in Delaware in December were larger and thicker walled than those found in summer. Later in the winter he tested the viability of conidia collected from the peach, plum, cherry, and quince. Many failed to germinate, but others produced vigorous germ tubes.

Cordley (*21*) found that conidia kept in a dry place for nearly two years failed to germinate. Conel (*18*) was able to germinate conidia from mummies collected as late as March 11, 1913, in northern Illinois, but not so late as April 12. Bartram (*9*) in 1916 reported on the effects of low temperature on the viability of the conidia. He tested the viability of conidia from plums hanging on the tree and in cultures placed in an open barn. Despite long periods of subzero temperatures, at times as low as −32° C., some conidia were viable as late as April 17. Cunningham (*24*) in New Zealand noted that conidia produced from mummies hanging on the tree during the winter months are slightly thicker walled than those produced during the growing period and are capable of remaining viable for several months, thus differing from summer conidia, which remain viable for only a short time—six weeks or even less.

The writers can confirm the statement that conidia are shorter lived during the summer than during the winter. The viability of conidia is greatly decreased by the unfavorable action of high temperatures. Conidia produced on culture media and kept at room temperature or somewhat higher are about as short lived as those produced naturally out of doors in summer. In germination trials made by the senior writer, cultures about 2 weeks old usually produced the highest percentage of viable conidia; but in summer, after a period when the laboratory temperatures were not lower than 90° F. for several successive days (much of the time about 98° and sometimes over 100°), it was difficult to find a viable conidium of any age. Transfers of masses of conidia to fresh media very commonly resulted in no growth.

MICROCONIDIA

No information is available concerning the viability of the microconidia. In fact, Humphrey (*46*) is the only investigator who claims to have germinated them, and he did not make any tests with microconidia of different known ages.

GERMINATION OF SPORES

ASCOSPORES

The ascospores when newly formed germinate readily in four to six hours, producing usually a single germ tube (pl. 2, C) which later branches. Many of the ascospores that fall back on the hymenial surface of the apothecium germinate in situ, producing the usual

germ tube, which, however, may soon give rise to the flask-shaped microconidiophores and microconidia. Sometimes the germ tube gives rise to these organs directly upon its emergence, and sometimes the microconidiophores seem to be developed directly from the ascospore without the production of a germ tube.

CONIDIA

The conidia germinate readily in distilled water and in most culture media. In sterile prune juice germination is very rapid, the germ tubes sometimes appearing within an hour when temperatures are at or near the optimum. In 24 hours growth is so profuse that if many conidia are present and germinating it is difficult to follow the development of individual germ tubes. The germ tube is comparatively straight and usually does not branch until it has become quite long. (Pl. 2, D.) Ezekiel (*34*) gives as typical a length of 113 μ before branching. Wormald (*105, v. 34, p. 166*) states: "* * * It is usually at least 200 μ in length before it begins to branch, and unbranched germ tubes 650 μ and 750 μ in length have been observed."

Especially in drops of distilled water, and apparently when conditions for germination are not near the optimum, separate germ tubes have been seen to fuse with each other and with conidia. (Pl. 2, E.) Often a number of conidia lying close together will be joined apparently by the end of a germ tube of one fusing with the end of another, or by the end of a germ tube fusing with a conidium.

Doran (*29*) reported that conidia of *Sclerotinia fructicola* germinate quite as well in sunlight (whether it be direct, diffuse, glass filtered, or not glass filtered) as in darkness. He concluded that conidia require precipitated moisture for germination, since none germinated on a dry slide in a moist chamber, but all those in a drop of distilled water germinated.

MICROCONIDIA

Humphrey (*46, p. 88–89*) states with regard to microconidia:

> When some of these spores are sown on nutrient gelatine they germinate readily, first swelling to double their former diameter, and produce abundant mycelia (fig. 8). * * * These spores were also found fallen from their attachments and beginning to germinate (fig. 6, *a*). * * * While these spores can germinate without nourishment, they suffer no preliminary increase in size. On prune-gelatine they swell and germinate as above described.

Humphrey's figures bear out his statements to some extent, but it is possible that the "swollen" spores may have been conidia rather than microconidia. Those in his Figure 8 greatly resemble conidia, but those in his Figure 6, *a*, appear to be true microconidia.

The writers have repeatedly tried to germinate microconidia in distilled water and in various nutrient fluids, but without success. The junior writer has placed masses of microconidia on the stigmas of fresh peach blossoms, thinking that they might need some special stimulus for germination. If they germinated, they did not produce any symptoms of infection on the blossom.

Hino (*43*), working with microconidia produced by several species of Sclerotinia, was unsuccessful in his germination tests except in a few rare cases. In the one case mentioned in the English résumé of

his paper, microconidia of *S. trifoliorum* Erikss., produced germ tubes 4 by 1 μ in size but developed no further.

Ramsey (*71*) states that approximately 10 per cent of his attempts to germinate microconidia of species of Sclerotinia attacking vegetables were successful. From the germinated microconidia he succeeded in obtaining only two cultures that developed a vegetative growth which could be recovered.

DISSEMINATION OF THE FUNGUS

In 1868, at a meeting of the Illinois Horticultural Society, Freeman (*38*) stated that Doctor Hilgard, of St. Louis, at a meeting of the American Association for the Advancement of Science at Chicago, had declared that the spores of peach rot float in the air, live in the ground, and thrive under conditions of warmth and moisture. Hilgard (*42*), in a publication of his own in 1869, stated:

> No doubt the subtle germ is widely diffused and most abundantly present on every healthy peach, since every drop of trickling rain may carry thousands of moist, rapidly infectious germs from the resoaked gum.

Smith (*91*) stated: "Rains, winds, birds, insects, etc., all help to disseminate the spores." Scott and Ayres (*87, p. 13*) stated: "The spores are undoubtedly distributed broadcast by the wind, so that they are in most cases ever present on the fruit * * *." Brooks and Fisher (*16*) also consider wind the important agent, with insects also playing a part. Cunningham (*24, p. 88*), in New Zealand, after stating that the conidia are carried to the fruits by winds, insects, or even birds, gives a specific instance of a bird [10] acting as a distributing agent:

> With their beaks, the birds commonly pierce infected fruits, and turn from these to healthy fruits, especially those showing color, such as nectarines, which in turn they puncture, probably with a view to ascertaining whether they are edible.

That wind, rain, insects, and birds are factors in the dissemination of the fungus in the orchard there can be little doubt. Of these, wind is undoubtedly the most important. One has only to disturb slightly a half-rotted fruit or a conidia-covered mummy to convince himself that wind is an effective agent of distribution. The myriads of conidia that rise as a dust or smoke are seen to float away in the air to be dispersed by the wind and doubtless carried long distances. The ascospores also are discharged as a dust which is with apparently equal ease dispersed by the wind.

Conidia collect about the periphery of drops of water and are easily splashed away by the falling of successive drops or are washed down by currents or trickles. Insects and birds distribute the disease to some extent by alternate contact with diseased and sound fruits. The plum curculio may even insert spores when puncturing sound fruits. The dreaded epiphytotics of brown rot are undoubtedly due in the main to the fact that the conidia are so easily and effectively distributed by air currents. After such a distribution,

---

[10] A small bird known locally at Weraroa, New Zealand, as silver eye or white eye (*Zosteropus lateralis* Latham).

optimum conditions of temperature and moisture as the fruit nears maturity are certain to bring about an epiphytotic of brown rot.

As pointed out by Quaintance (*70*), in the gathering of fruit for shipment there is a general scattering of conidia. Mummied and rotten fruits are disturbed, and the pickers' hands become covered with conidia, which are rubbed over sound fruits. In this way the fruit becomes covered with conidia, which may initiate the disease in the packing shed, in transit, or on the market.

HOST PLANTS

A list of host plants can not be considered complete, since there has been no attempt to make a survey of these plants, and can not be considered accurate, because of the confusion that has existed regarding the classification of this and closely related species of Sclerotinia. Under favorable conditions the fungus is probably able to infect all drupaceous and pomaceous species as well as many other members of the Rosaceae. The following list has been assembled from the literature and from the writers' observations.

Chaenomeles japonica Lindl	Flowering quince.
Cydonia oblonga Mill	Common quince.
Malus pumila Mill	Apple.
Prunus americana Marsh	American plum.
P. americana × *P. hortulana*	Plum.
P. americana × *P. salicina*	Do.
P. angustifolia Marsh	Chickasaw plum.
P. avium L	Mazzard.
P. avium × *P. cerasus*	Cherry.
P. armeniaca L	Apricot.
P. besseyi Bailey	Bessey cherry.
P. besseyi × *P. hortulana*	Compass plum.
P. besseyi × *P. pennsylvanica*	Plum.
P. besseyi × *P. salicina*	Do.
P. cerasus L	Sour cherry.
P. communis Arcang	Almond.
P. domestica L	Common plum.
P. fenzliana Fritsch	Almond.
P. glandulosa Thunb	Flowering almond.
P. hortulana Bailey	Hortulan plum.
P. instititia L	Damson plum.
P. japonica Thunb	Chinese bush cherry.
P. mume Sieb. and Zucc	Japanese apricot.
P. munsoniana Wight and Hedr	Wildgoose plum.
P. nigra Ait	Canada plum.
P. pennsylvanica L	Pin cherry.
P. persica Batsch	Peach.
P. persica var. *nucipersica* Schneid	Nectarine.
P. pumila L	Sand cherry.
P. pumila × *P. pennsylvanica*	Do.
P. reverchonii Sarg	Hog plum.
P. salicina Lindl	Japanese plum.
Prunus sp	Rocky Mountain dwarf cherry.
P. tomentosa Thunb	Nanking cherry.
P. triloba Lindl	Flowering plum.
P. umbellata Ell	Southern sloe.
P. virginiana L	Common chokecherry.
Pyrus communis L	Pear.
Rosa sp	Rose.
Rubus occidentalis L	Common blackcap.
Rubus sp	Blackberries.

SEASONAL LIFE HISTORY AND PATHOGENICITY OF SCLEROTINIA FRUCTICOLA

Investigations of the seasonal life history and pathogenicity of the brown-rot fungus have engaged the attention of many botanists and plant pathologists since 1880. Previous to that time Hilgard (*42*), Kirtland (*49*), and probably others, as pointed out earlier in this bulletin, had some knowledge of the pathogene and its behavior.

For the sake of convenience the discussion of the seasonal life history and pathogenicity will be grouped under several headings and subdivisions. It should be clearly realized that such a division is purely artificial and that the various activities of the fungus proceed concurrently or overlap.

SURVIVAL IN WINTER

After it became clearly recognized that the common rot of the peach was caused by a fungus, plant pathologists began a search for the means whereby the fungus could survive the unfavorable conditions of winter. As a result it has been found that the fungus can pass the winter in a resting stage (1) on mummies hanging on the tree, which produce conidia in the early spring and on which also many conidia produced the previous season may survive, (2) on mummies lying on or in the ground, many of which may produce the apothecial stage at blossoming time, and (3) in cankers on twigs and branches, from which conidia may or may not be produced the following season.

SURVIVAL THROUGH FORMATION OF CONIDIA ON MUMMIES

Arthur (*5*) appears to have been the first to show that conidia from mummied fruits of the previous year could act as infection sources. He germinated conidia from such sources (mummied cherries) and showed that they could cause disease. He states (*5*, *p. 281*):

> When the fruit is attacked before it is ripe, it usually remains hanging to the tree through the winter, even till fruit is ripe again, and spores of the fungus are to be found on it during the whole time.

Similar results with cherry were obtained by Galloway (*39*).

Smith (*91*) seems to have been the first to show that peach mummies hanging on the tree produce new crops of conidia in the early spring that are capable of germinating and causing infection. He also showed that conidia can survive the winter. These results were soon confirmed by Humphrey (*46*) and by Chester (*17*). Bartram (*9*) demonstrated the viability of a fair percentage of conidia that had passed through winter temperatures as low as −32° C.

Most brown-rot mummies become loosened and drop to the ground of their own weight or are blown loose by the wind, but there are always some that remain hanging on the trees through the winter and early spring.

Since the brown-rot fungus completely invests the outer tissues of the peach during the formation of the mummy and forms a sclerotial membrane, it can withstand long periods of adverse environmental conditions and still produce fruiting bodies. Mummies hanging on the trees produce conidia only, whereas those on the ground produce

apothecia and rarely, if ever, produce conidia; but Valleau (*97*) found that mummied plums that have hung on the tree for one year still have the power of producing apothecia when buried in the ground. Mummies on the ground are frequently the more reliable source of infection at blossoming time, because many of them retain sufficient moisture to produce apothecia even in a dry spring.

It is possible to demonstrate the survival of the fungus in mummies by removing the inner tissue of the mummies under sterile conditions and obtaining cultures of the fungus from it; but the demonstration that the fungus is alive is not the essential point. It not only must remain alive but also must produce spores for it to be considered an effective agent in the spread of brown rot.

In Georgia the writers observed periods of conidial production from mummies hanging on the trees in every month from September to February in the years 1921 to 1925. February 17 was the latest date on which conidial production was observed. The production of conidia is closely correlated with periods of rainy weather and, as the above dates indicate, takes place at relatively low temperatures provided sufficient moisture is present. The percentage of mummies that produce conidia is at times very high. On November 11, 1921, 95 to 98 per cent of the peach mummies (variety Early Wheeler) hanging on the trees bore fresh tufts of conidia. (Pl. 2, F.) On December 31, 117 of a total of 132, or 91 per cent, of the same variety were producing conidia. On September 18, 1924, 75 per cent of the Elberta and 69 per cent of the Yellow Hiley mummies out of a total of 100 collected from each variety were producing conidia. On the other hand, in some seasons conidial production by mummies on the trees is rare. Peach and plum mummies collected by the senior writer in the winter of 1920 from trees at the Arlington Experiment Farm, Rosslyn, Va., rarely produced conidia when placed in moist chambers, although in other years they have usually done so.

Although the writers have examined mummies from most sections in which brown rot occurs, they have never observed production of conidia by mummies on the ground, nor have they been able to induce conidial production by placing these mummies in moist chambers. Just why these mummies should not produce conidia as well as ascospores is not known.

It is evident from the observations of many investigators that the fungus may remain alive in mummied fruits on the tree and on the ground and that many of those on the tree are capable of producing conidia for many months. By late spring, mummies on the tree, becoming dried, cease to produce conidia and, falling to the ground, soon disintegrate.

SURVIVAL THROUGH FORMATION OF APOTHECIA FROM MUMMIES

An important phase in the development of the fungus from overwintering sources is the formation of apothecia from the sclerotia enveloping the mummied fruits that have fallen to the ground. Norton (*59*) in 1902 made the most important single contribution to the life history of this fungus when he showed that these apothecia represent the ascigerous stage of the brown-rot fungus. For nearly 20 years after Norton's discovery it was generally accepted that mummies had to lie on the ground through two winters before

apothecia were produced; but, as has been shown by Roberts (*76*), Ezekiel (*32*), and Cunningham (*25*, *26*), apothecia may develop in the spring from fruit that had rotted and fallen to the ground during the previous summer or autumn. The observations and experiments of the writers reported later in this bulletin indicate that in most seasons apothecia are formed in much greater abundance from rotted fruits that have lain on the ground through only one winter than from those that have been exposed two or more winters. However, the importance of the production of apothecia from the older mummies should not be overlooked. The apothecia from the older mummies aid in reestablishing the fungus in the orchards following seasons in which there are no newly formed mummies because of the failure of the trees to bear or because conditions for infection are unfavorable.

SURVIVAL IN CANKERS ON TWIGS AND BRANCHES FROM WHICH CONIDIA MAY OR MAY NOT BE PRODUCED THE FOLLOWING SEASON

The status of cankers as carriers of the fungus over winter and producers of conidia the following season is somewhat uncertain. That the fungus survives the winter in some of the cankers has been shown by many investigators, but few have observed the production of conidia on overwintering cankers. Smith (*91*, *p. 131*) in 1889 stated:

> As a rule the fungus produces its conidial tufts much less frequently on stems than on fruit. Occasionally I have seen them on branches of the previous season's growth, but generally they are more abundant on tissues only recently out of the meristematic condition * * *.

Quaintance (*70*) states that the fungus is capable of developing the spore tufts from blighted fruit spurs and twigs of the previous year but does not state that he observed such development in orchards. Cook (*19*) in 1919 observed the production of conidia from cankers of the previous year and considered them as important in the production of blossom blight. Cunningham (*24*) also considered cankers of the previous year important infection centers. Berkeley (*10*) reports that at St. Catharines, Ontario, in the spring of 1926, many cankers were active and conidia were present on them. He found active 2-year-old cankers and concluded that possibly cankers are sources of infection for the blossoms of the following year.

Only once have the writers observed the formation of conidia on overwintering cankers, although they have made observations as opportunity presented over a period of about 10 years. It would appear that, as compared with mummied fruits, cankers are not of great importance as overwintering sources of infection, except perhaps in certain sections where weather conditions favor the continued development of cankers and conidial production from them. The formation and persistence of cankers will be discussed subsequently.

OCCURRENCE OF APOTHECIA

As pointed out by Norton (*59*), the duration of apothecial production is about that of the peach flowers. It is interesting to observe how closely these two periods coincide over a term of years. In eight years' (1920–1927) observations at the Arlington Experi-

ment Farm near Washington, D. C., the time of full bloom of Elberta peaches varied from March 20 to April 21, with apothecial production showing practically the same variation. Norton, Ezekiel, and Jehle (*60*) have also noted that the production of apothecia coincides with the germination of peach and plum seeds lying under the trees.

Apothecia may be produced in considerable numbers. McCubbin (*54*) found 111 in one cluster and a total of 1,163 clusters under 225 peach trees, an average of 5.1 to the tree. In one peach orchard there were 26.3 clusters to the tree. Leslie Pierce, of the Bureau of Plant Industry, has informed the writers that in Indiana in 1927 he found 87 clusters under one peach tree.

The sclerotia investing mummied fruits are quite persistent and may produce apothecia for many years, although the crop usually becomes less with each succeeding year. Pollock (*68*) found apothecia produced from plum mummies that had lain on the ground for 10 years. Ezekiel (*36*), however, has shown that mummies when buried in the ground, a condition that would obtain in most orchards, disintegrate very rapidly.

In the fall of 1921 the writers started a series of experiments at Fort Valley, Ga., to determine how long apothecial production would continue. Peach mummies of the 1921 crop were picked from the trees and buried in sandy clay soil at depths varying from one-half inch to 3 inches. There were no peach trees in the vicinity, but as a safeguard against the accidental introduction of other mummies wire cages were placed over the different lots of mummies. Apothecia were produced in abundance in the spring of 1922 and in slowly diminishing numbers each successive year until the spring of 1928, when none developed. In these experiments mummies of known ages (i. e., of the 1921 crop) produced apothecia for six successive years.

Brooks and Fisher (*16*) have observed that with prunes and cherries apothecia occur chiefly on mummies near the surface of the soil and are rare or lacking in orchards in which mummies are regularly plowed under. Ezekiel (*32*) showed that cold is probably a factor in the production of apothecia, since chilled mummies produce apothecia 25 weeks after inoculation. He also showed that burying mummies beneath the surface of the ground inhibits the production of apothecia, even if production had started when the mummies were buried. He (*33*) found that apothecia developed best at pH 2.5 and made good growth from pH 1.4 to 5.8, but that even slight alkalinity inhibited growth.

Cunningham (*26*, *p. 228*) in New Zealand considered the following as favoring apothecial production:

(1) Showery weather accompanied by warm days and cool nights.
(2) Depth at which mummies are buried. The number of apothecia produced decreased with the depth of the soil.
(3) Age of mummies. Those of the past season produced apothecia most abundantly.
(4) Soil conditions. Apothecia were more abundant in compact than in loose soil.

In general the observations of the writers are in agreement with those reviewed above. The largest crop of apothecia is, under favorable conditions, produced by mummies 1 year old and it decreases with age. At the Arlington Experiment Farm, a growth of chick-

weed (*Cerastium vulgatum* L.), which begins very early in the season, has always favored apothecial production, probably because it prevents the mummies from becoming dry by shading them.

The experiments of the writers in which yearly observations were made on peach mummies buried at various depths have indicated that, as others have found, the best position for apothecial production is that in which the mummy is only half buried, the apothecia arising from the under surface. Mummies entirely exposed on the surface of the soil uniformly failed to produce apothecia. (Pl. 3, A.) Completely buried mummies may produce apothecia which appear in abundance at the surface of the soil, but they are frequently destroyed by earthworms, and those that escape destruction often produce distorted apothecia. Stipes 6 cm long have been observed arising from deeply buried mummies.

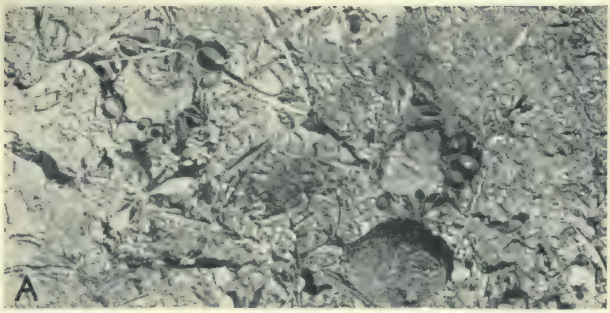
Buried mummies tend to break up as they increase in age, and only fragments of the sclerotia remain. These fragments still possess the ability to produce apothecia. (Pl. 3, B.) In one instance a fragment measuring 3.8 by 1.4 cm was found on which 15 small apothecia were produced. In another instance three apothecia of about average size were produced from a bit of sclerotium 1 cm long and 2 mm wide. Apparently there is a fairly definite period during which mummies must be in the soil before apothecia are produced. Mummies collected from trees in November and buried have produced apothecia within 70 days, but mummies collected in August and kept dry until the following February and then buried failed to produce apothecia in March. The sclerotia had not been killed by the drying process, as apothecia developed from them the following spring. In the vicinity of Washington, D. C., the larvae of the oriental fruit moth (*Grapholitha molesta* Busck) in the decayed fruits appear to aid in the disintegration of mummies.

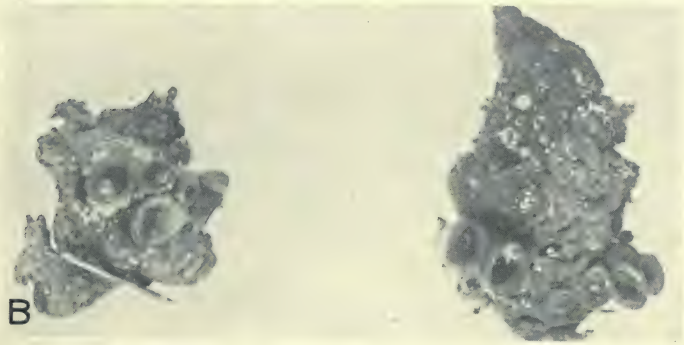
Apothecia have been reported as occurring on mummied fruits of most of the drupaceous hosts but appear rarely to be produced from mummied fruits of pomaceous hosts. The only authentic record of the production of apothecia from mummied apples appears to be that of Harrison (*40*) in Australia. He obtained apothecia from partly buried apple mummies, and single ascospore cultures from them were pronounced by Wormald to be identical with cultures of *Sclerotinia fructicola* (called by Wormald *S. americana*).

DISCHARGE OF ASCOSPORES

The ascospores are discharged by pressure within the ascus, and the simultaneous discharge of many asci from a single apothecium produces a dust or cloud easily discernible to the naked eye. This discharge may be artificially induced by sudden exposure to light or by intensifying the light. Petri dishes of potato agar held over apothecia puffing out clouds of spores are quickly seeded. In a closed room the writers have caught spores in Petri dishes held as high as 20 inches above the discharging apothecia. At this height, however, it is probable that ascending air currents played a considerable part.

The writers have also measured the distance above the surface reached by spores discharged from an apothecium inclosed in a small box when a beam of light played over the surface of the





SCLEROTINIA FRUCTICOLA AND BLOSSOM BLIGHT

A, Apothecia developing from two partially buried mummies. No apothecia have developed from the third mummy, which is resting on the surface of the soil. Slightly reduced. B, Apothecia produced in the spring of 1923 from small fragments of a mummy of the 1921 crop. Natural size. C, Blossom blight of the peach, Elberta variety. Note the stiff matted appearance of the floral parts of the infected (uppermost) blossoms. Natural size.

BROWN ROT OF PEACH AND WILD HOST OF SCLEROTINIA FRUCTICOLA

A, Brown rot of a mature Uneeda peach. The source of infection was the blighted blossom located just above the rotted peach. Natural size. B, Extensive thicket of wild plum (*Prunus angustifolia*) observed near a peach orchard in central Georgia. Apothecia were very abundant under the trees in this thicket in the spring of 1928. Plum thickets such as this constitute a distinct menace to near-by orchards.

apothecium to reveal the spores. The spore discharge was observed through a slit in the box, and the height of the discharge was measured by placing a metric rule behind the apothecium. The placing of the apothecium in the box counteracted, to a certain extent at least, the effect of convection currents, and the measurements may be considered as rough approximations of the actual distances the spores are shot above the apothecium under the sole influence of forces in the ascus. The average height of spore discharge in the 31 measurements was 1.7 cm. The highest discharge observed was 4.3 cm and the lowest 0.5 cm.

Individual apothecia have been collected which produced clouds of spores at intervals for as long as seven days.

In order to determine whether ascospores were prevalent in the air, Petri dishes containing potato agar were exposed in a field which had been an orchard until two years before and in which there were scattered clumps of half-buried mummies producing apothecia. Two dishes placed on the ground and exposed for three minutes developed eight and two colonies, respectively, of the brown-rot fungus. Two dishes exposed for three minutes at a height of 4 feet above the ground each developed one colony of the fungus. So far as could be ascertained, there was no production of conidia from any source, and the colonies were assumed to result from ascospores.

THE BLOSSOM-BLIGHT PHASE OF THE DISEASE

Arthur (*5*) observed blossom blight of cherries in 1886 and produced it artificially by inoculating cherry blossoms with conidia. In 1889 Galloway (*39*) published a detailed description of the disease and called attention to the importance of the blighted blossoms as sources of infection. Smith (*91*, *92*) in 1889 and again in 1891 called attention to the serious nature of blossom blight in the peach orchards of the Delaware-Maryland-Virginia Peninsula. Although Arthur in 1886 had shown that conidia of the brown-rot fungus could infect cherry blossoms, Chester (*17*) in 1893 seems to be the first to announce the production of peach-blossom blight by artificial inoculation. Since that time Quaintance (*70*), Scott and Ayres (*87*), Jehle (*48*), McCubbin (*54*), Cook (*19*), McClintock (*52*, *53*), and others have discussed blossom blight of the peach. Roberts and Dunegan (*78*) in 1926 reported on inoculation experiments of peach blossoms with conidia and ascospores. Both spore forms proved capable of causing blossom blight. All parts of the open flower could be attacked, and infection of the stigma, anthers, petals, and sepals was observed.

With the infection of blossoms in the spring by conidia or ascospores from diseased material that has survived the winter, the fungus makes its first attack of the growing season. The first symptom of infection is a faint discoloration of the part affected, whether it be the petals, stamens, or stigma. The fungus grows rapidly, and the entire floral structure is soon brown and shriveled. Masses of spores are produced on the diseased blossoms. The petals, styles, and filaments of the blighted blossoms become matted together in a dry, brittle mass generally bending downward. (Pl. 3, C.)

The sepals may be and generally are involved in the blighting of the other floral parts, and may be covered with spore tufts when the

young peach is the size of a pea. Usually, but not always, the infected sepals drop to the ground without the fungus gaining entrance to the young fruit.

Galloway (*39*) reported that blighted cherry blossoms remained on the trees three or four weeks; then, if the weather was wet, they dropped from the tree; and, being a mass of soft rotted tissue, they adhered to any part of the tree they touched. In Georgia many of the blighted blossoms are dislodged by various agencies, but the writers have not seen cases in which these dislodged blighted blossoms per se produced infections on either fruit or leaves, nor have they seen them attached to any portion of the tree. On the contrary, they have found blossoms remaining attached to the twigs as late as January of the year following their production.

In humid sections blossom blight is usually present to some extent every year and under favorable conditions may become very prevalent. Its development is favored by the moist, moderately warm weather often encountered at the time peaches are in bloom. Usually blossom blight is not noticed until the blooming season is nearly over, when the browned flowers begin to attract attention.

While blossom blight may cause severe losses by reducing the number of flowers capable of developing into fruits, it more frequently causes severe damage, not so much by reducing the set of fruit as by establishing in the orchards numerous sources of infection which later make it more difficult to prevent the fruit from rotting.

THE FRUIT-ROT AND MUMMY PHASE OF THE DISEASE

The fruit rot or so-called brown rot of the peach is essentially a ripe rot, or rot of the maturing fruit, although the fungus may enter young green peaches through punctures or bruises and cause rot. There are exceptions to this statement. In May, 1924, about three weeks after petal fall and following two weeks of wet weather, the senior writer observed young fruits, about the size of peas, which had been killed by brown rot. Examination of these fruits showed that infection had come about through contact with the closely appressed calyx which had become infected.

Conidia of the fungus are carried over to the maturing fruits from the last year's mummies, green fruits, blighted blossoms (pl. 4, A, and pl. 5, C), and twig cankers of the current year mainly by wind, but to some extent by rain. Leaves affected by leaf curl (*Exoascus deformans*) are also frequently important as sources of infection, as has been observed by McCubbin (*54*) and by Mix (*57*). Early in June, 1920, the senior writer examined an orchard heavily infested with leaf curl. Conidial tufts of the brown-rot fungus were found on nearly every affected leaf examined. It could hardly be doubted that the fungus would be carried over to the ripening fruits from these leaves.

Many investigators, including Smith (*91*) and Chester (*17*), have demonstrated that infection can take place through the uninjured epidermis of fruits but that infection is easier and more common when the surface is bruised or the epidermis punctured. Soft overripe and watery fruits are more easily infected than are the more solid ones. Most commercial varieties of the peach are not so easily infected through the unbroken epidermis as are many of the more

delicate noncommercial varieties. With commercial varieties most of the infections in the orchard take place through punctures made by the plum curculio (*Conotrachelus nenuphar* Hbst.), the oriental fruit moth (*Grapholitha molesta* Busck), and other insect pests, or through cuts or bruises made by hail or other mechanical agencies. As shown by Smith (*91*), the fungus may enter also through lesions made by the scab fungus (*Cladosporium carpophilum* Thüm.).

According to Curtis (*27*), the fungus is able to penetrate the cuticle of plums, cherries, nectarines, peaches, and apricots, but the usual method of effective entry is, in the case of peaches, through the hair sockets. She also observed a considerable number of infections through the stomata. Valleau (*97*), experimenting with plums, found that infection may take place through the uninjured skin at any time during the development of the plum fruit. The hyphae enter through the stomata and lenticels. Varieties show great differences in resistance to infection, owing to the production of parenchymatous plugs which may gill the stomatal cavity, and of lenticels with layers of corky cells through which the hyphae are unable to penetrate. Corky cells lining the stomatal cavity merely delay infection. Valleau also states that the rot is a firm rot due to the mechanical support of the hyphae which completely fill the intercellular spaces left by the collapse of the host cell walls.

Under favorable conditions the incubation period is very short. Chester (*17*) places it at 18 hours. Quaintance (*70, p. 256*) states:

> Spores inserted under the skin of a ripening peach with a needle point developed the usual brown rotten spot, an inch or more in diameter, in 20 hours, and the production of spore tufts followed 3 hours later, thus making the period of reproduction from the spore, under very favorable conditions, at 23 hours.

Conidia produced on infected fruits may be carried by the wind or other agencies to other fruits on the same or neighboring trees and by infecting them cause the disease to spread rapidly.

The fruits when thoroughly invested by the ramifications of the fungus hyphae become dried and may continue to hang on the tree or may fall to the ground. Many of the peaches that fall to the ground do so before they are completely rotted, while those left on the tree frequently remain attached because, since the fruit stem has been killed by the fungus, no abscission layer is formed. The completely rotted and shriveled fruits on the tree and on the ground are the so-called mummies, which are so important in initiating the disease the following spring through the agency of conidia or ascospores produced by them.

THE CANKER AND TWIG-BLIGHT PHASE OF THE DISEASE

The formation of twig cankers as the result of the fungus passing from the floral parts through the peduncle and into the tissues of the twigs is frequently a sequel to blossom blight. Occasionally twig cankers result from growth of the fungus through the stem of decayed fruit and into the twig, but this more often results in a blight of the twig rather than in the formation of cankers. Although cankers and blighted twigs do not necessarily occur every year, they are usually present, because the climatic conditions that are favorable

to blossom blight and fruit rot also favor the growth of the fungus into the twig tissues.

Twig cankers resulting from the growth of the fungus through the blossom peduncle into the tissues of the twig appear first as slightly browned, collapsed areas about the base of the peduncle. (Pl. 5, A.) They are roughly elliptical in shape and at first involve only the portion of the twig adjacent to the blighted blossoms, but by subsequent growth the fungus extends up and down the twig from the original point of entrance. The development of a number of these cankers was followed in the spring of 1923, and it was found that they may increase in length as much as 4.1 cm in a period of 30 days during the early spring. (Table 4.) This rate of growth, however, is not maintained throughout the growing season.

TABLE 4.—*Increase in length of brown-rot twig cankers in 30 days*

Canker No.	Size of canker		Increase	Canker No.	Size of canker		Increase
	Mar. 14, 1923	Apr. 14, 1923			Mar. 14, 1923	Apr. 14, 1923	
	Cm	*Cm*	*Cm*		*Cm*	*Cm*	*Cm*
1	3.9	5.8	1.9	6	2.5	3.0	0.5
2	1.9	4.9	3.0	7	2.4	6.5	4.1
3	2.2	2.5	.3	8	2.6	3.1	.5
4	1.5	5.9	4.4	9	.7	1.0	.3
5	2.5	5.6	3.1	10	.9	1.0	.1

Gum pockets (pl. 5, B, and pl. 8, C) are formed in the tissue by the fungus, and in rainy periods the gum collects on the surface in the form of small droplets which may expand into large masses through the absorption of water by the gum. (Pl. 5, A and C.)

In rainy seasons the fungus frequently encircles and kills the twig above the canker by girdling. (Pl. 5, D.)

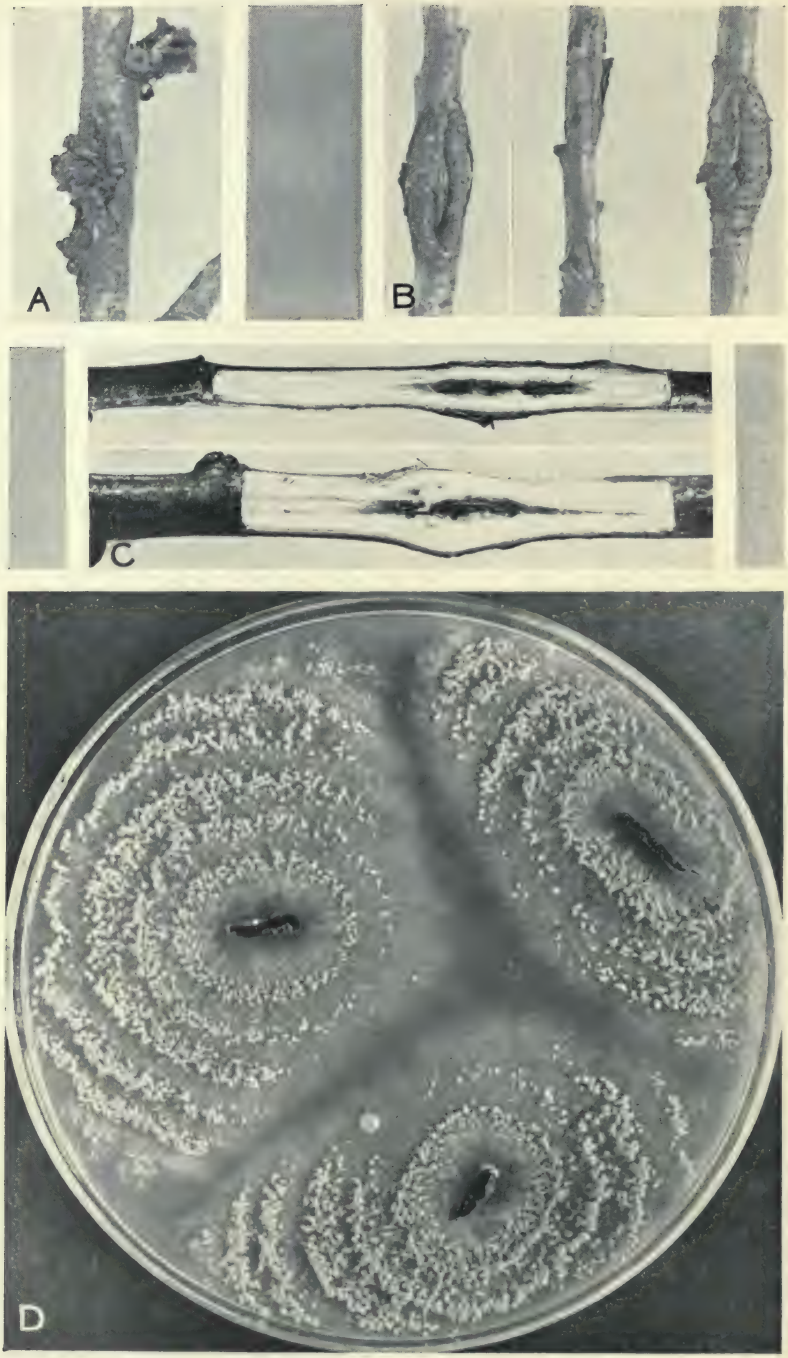
As the season advances, the central portion of the canker becomes bleached in color and the sunken bark is ruptured by the growth of callus tissue from the sides, so that, at the end of the growing season, the cankers are represented by distorted regions on the twigs. (Pl. 6, A.)

The callus tissue may cover the cankered area by the end of the season in which the canker originated, or the union may not be completed until the second growing season. (Pl. 6, B.) The final result is the covering of the necrotic area by new tissue and the formation of normal tissues following the union of the callus. The necrotic region is merely buried under a layer of new tissue and can be demonstrated in after years by cutting through the twigs. (Pl. 6, C.)

Almost all investigators are agreed that the cankers about the blossoms are the result of the fungus passing from the floral parts into the tissues of the twigs. Cook (*19*), in New Jersey, however, considered that the cankers were formed at the bases of the buds of the young shoots and therefore are at the bases of the flower buds that open the following spring. He found conidia produced on these cankers in the spring, but he did not give any data as to when and how these cankers were formed originally. Cook's description of

TWIG BLIGHT OF THE PEACH CAUSED BY SCLEROTINIA FRUCTICOLA ON UNEEDA VARIETY

A, Small twig. A drop of gum is oozing from the infected tissues. B, Twig canker with the outer tissues cut away to show necrotic region. The dark vertical line at the left represents a gum pocket. C, Large mass of gum adhering to canker on twig. D, Killing of apical portion of twig by the fungus girdling the twig below the blighted blossom. All natural size.



TWIG CANKERS OF THE PEACH CAUSED BY SCLEROTINIA FRUCTICOLA

A, Appearance of twig canker on Uneeda variety at the end of the growing season in which it was initiated. Photographed October 11, 1923, natural size. B, Twig cankers showing varying amounts of callus development. On the left the callus has not united; in the middle twig it has almost met; while in the twig at the right the callus tissue from both sides has united, completely covering the necrotic region. Hiley variety, photographed February 29, 1928, natural size. C, Twig cankers formed in 1927 cut open in February, 1928, showing the original necrotic area embedded in new tissue generated by the callus layer. Natural size. D, Petri-dish culture 15 days old with colonies of *S. fructicola* which have developed from fragments of the inner tissues of twig cankers. Slightly enlarged.

these cankers, his photographs of them and their position, i. e., just below the buds, suggest that they were cankers caused by arsenical sprays. These sprays commonly cause necrotic areas to form at the base of the petioles which appear the following spring as cankers at the base of the buds and often involve the buds. It is possible that the brown-rot fungus might gain entrance to the tissues after they have been ruptured and produce conidia the following spring. The writers doubt that the cankers described by Cook were caused by the brown-rot fungus, although they do not wish to imply that the organism was not present in them and that such cankers, caused presumably by arsenical injury and subsequently invaded by the brown-rot fungus, might not play an important rôle in the dissemination of the fungus.

Frequently the twig to which an infected peach is attached is invaded and killed. These dead twigs and accompanying cankers have received considerable attention from investigators of peach diseases. As early as 1868 the following statement by E. S. Hull, a prominent fruit grower of Alton, Ill., appeared in the Transactions of the Illinois Horticultural Society for that year (*45, p. 265*):

> These [fruits], under certain conditions, rot to such an extent, especially some of the early peaches, as to defoliate and kill all the interior branches, and so impair the vitality of the trees as to render them worthless, and, in some instances, to kill them.

On the plum the killing of spurs and adjoining bark was noted by Kirtland (*49*), who wrote in 1855: "This malignant and cankery action will, likewise, extend to the adjoining bark wood and fruit spurs; and often either entirely destroys their vitality or induces a sickly condition." Smith (*92*), Chester (*17*), and others also observed that the fungus by growth through the fruit stem and bark caused cankers and girdling of the twigs.

Because the brown-rot fungus attacks only the tissues that are not far beyond the meristematic stage, it seldom if ever causes cankers by direct infection of twigs or branches of the commonly planted commercial varieties. Even infection through wounds seems to be a rare occurrence. Many of the older varieties were abandoned because of their susceptibility to brown rot, and doubtless the shoots of some of them could become infected as Chester (*17, p. 61*) suggested in 1893:

> That infection through the bloom and the fruit is the usual method can not be denied, but the fact that trees have been found which have not blossomed and yet which show genuinely blighted twigs indicates that in some cases the fungus can find entrance other than already indicated. My own observations on this point lead me to believe that the tender opening buds of young shoots offer a favorable harbor for the developing fungus, which subsequently appears as a wilting of the young leaves and a blighting of the generally short terminal growths.

Smith (*91, p. 131*) first stated: "In the early spring the young and tender shoots must be infected by spores. Many such shoots were attacked and killed in 1889." Later he (*92, p. 37*) changed his mind and stated: "Heretofore I had supposed it capable of penetrating through the unbroken cuticle of young shoots, but such cases must be exceptional." Jehle (*48*) found it easy to inoculate twigs and branches of all ages through wounds, but concluded that natural infection of limbs occurs either through diseased blossoms

or through diseased fruits. Fant (*37*) concluded that infections take place through wounds as well as through infected blossoms and infected fruit.

The writers have not seen in commercial peach orchards a twig or branch lesion in which the brown-rot fungus was growing that could not be traced to a blighted blossom or to a mummied fruit. They have seen blighted twigs of noncommercial varieties that appeared to have been directly infected through spores.

Jehle (*48*) reported that cankers live over and increase in size from year to year. Although a callus layer forms about these cankers each year, it also may become infected. Smith (*90*) found lesions on stems producing conidial tufts occasionally during their second year. McClintock (*52*) in Georgia and Cunningham (*24*) in New Zealand stated that these stem lesions may produce conidia during the following spring and consider them important as infection centers. In Delaware, Manns and Adams (*55*) reported that the fungus survived the winter of 1921–22 in 75 per cent of the cankers on the Carman variety examined, but that there was no evidence of survival in blossom-blight cankers on the Belle and Elberta varieties. Brooks and Fisher (*16*) were unable to find conidia on cankered limbs of prunes, although a careful search was made. Berkeley (*11*) in Canada reported that in the spring of 1926 many cankers were active and spores were present in them. He also found active 2-year-old cankers.

It has been the writers' experience that the fungus frequently does not live over in blighted twigs and cankers. In March, 1925, at a time when in northern Virginia mummies were producing conidia in large numbers, 19 cankers that had formed about these mummies were collected, and in no case was there a development of the brown-rot fungus from the cankers, although it developed readily from the fruit stems. McClintock (*53*) in the season of 1929 was unable to find conidia produced in such cankers, although he examined hundreds of them. McCubbin (*54*) in Canada was unable to obtain cultures of the brown-rot fungus from dead twigs and cankers on which mummies were found, and he concluded after experimentation that the killing was caused by juice from the rotted peaches passing into the twigs.

Beginning in 1923 the junior writer investigated the longevity of twig cankers in Georgia, particularly those following blossom infections. When the inner tissues of young cankers, collected in April, were removed under aseptic conditions and placed on potato-dextrose agar in Petri dishes, pure cultures of the organism were readily secured. (Pl. 6, D.) Similar results were obtained during May. In August many of the cankers had ruptured, and numerous contaminations developed in cultures from the tissue fragments, but the brown-rot fungus was also obtained in each trial. The experiments were continued during September, October, and December. In these months the number of tests in which the brown-rot organism was not secured increased each month, and in December the organism was secured from only one canker in a series of eight tested. No experiments were performed in 1924, and blossom blight was not severe in 1925 and 1926, so that the twig cankers were not abundant. Blossom blight was severe again in 1927, and work on a larger scale

was started with the cankers that developed that year. Since the earlier work had shown that the organism was alive in a certain number of cankers until December at least, cankers were not examined until January, 1928. One hundred and five cankers were collected at intervals during January and February before the trees started to blossom. Fragments of the interior portion of each canker were removed under aseptic conditions and placed on plates of potato-dextrose agar. The brown-rot organism was secured from 41 cankers, or 39 per cent of the total number. In each case a record was kept as to whether the canker was still open or whether the callus tissue had closed over the original necrotic area. In addition a record was kept of the location of the tissue used in each test, whether from the apical, central, or basal portion of the canker. These data are summarized in Table 5. A higher percentage of successful isolations of the brown-rot fungus was obtained from tissues taken from the center of the cankers than from the apical and basal portions, and also a higher percentage of isolations was obtained from those cankers that were not covered by callus.

TABLE 5.—*Results of attempts to isolate Sclerotinia fructicola from different parts of twig cankers—January and February, 1928*

Part of canker	Cankers used	Cankers from which fungus was isolated	
	Number	*Number*	*Per cent*
Apex	28	11	39
Center	49	22	45
Base	28	8	28
Necrotic region covered by callus tissue	38	5	13
Necrotic region not covered by callus tissue	67	36	54

Blossom blight and twig cankers were prevalent in Georgia again in 1928, and the experiments of the previous year were repeated during February and March, 1929. Fifty-four cankers were studied during this period, and the fungus was isolated from seven of them.

In addition to the isolation studies, field observations were made in 1923, 1924, and 1925 for evidence of the production of conidia on overwintered cankers. No conidia were observed on overwintered cankers, although production of conidia is not particularly uncommon during the season in which the cankers are initiated. In March, 1928, 100 cankers on the trees of the Hiley variety in an orchard near Fort Valley, Ga., were selected at random and tagged. These cankers were the result of blossom infection in 1927. Blossom blight appeared in the orchard on March 28, signifying that the fungus was active, but a careful examination of each canker with a hand lens failed to reveal any signs of spore production on the surface of the cankers.

On April 12, after a rainfall of 2½ inches, two spore tufts were found on one canker. Germination tests showed that the spores were viable. Additional examinations were made during the rest of the season, but spore tufts were not observed on any of the cankers. The canker which produced conidia on April 12 was of the open type, i. e., one in which the callus layer had not united.

From these isolation studies, extending over a period of six years, it seems evident that the fungus remains alive over winter in a certain percentage of the twig cankers each year. This fact would be more important if the field observations during the same period had not failed to reveal the production of spore tufts (with one exception) on the cankers. The survival of the fungus in the tissues of the twig without the production of the spores is of no importance so far as the spread of the disease is concerned. These conclusions, based on studies in Georgia and Virginia, may not be applicable to all peach-growing sections. Under different environmental conditions it is possible that the cankers may assume a more important rôle in the spread of the disease.

LEAF INFECTION

Leaves that have been killed by the brown-rot fungus are common enough, but the number of leaves killed is so slight that the reduction in total foliar surface is inconsequential. Under optimum conditions for infection, leaves may be attacked and the fungus may be found fruiting in brown spots which later may be excised. More frequently the entire leaf is involved, as when the fungus enters from a blossom-blight or a mummied-fruit canker through the petiole, or when a leaf, coming into such close contact with a rotting or mummied fruit that the exudate from the rot causes it to adhere closely, becomes infected throughout.

In moist weather the fungus may enter leaves injured by other agencies, especially by the leaf-curl fungus, *Exoascus deformans*. Like the blighted blossoms, twig cankers, and early-infected fruits, leaves infected early in the season aid in the dissemination of the fungus and help to provide an abundance of conidia that may infect the ripening fruit.

RELATION OF INSECT PESTS TO INFECTION

Although insect pests are probably of little importance in the dissemination of the disease, they are of great importance as agents that produce wounds in the fruit, through which infection readily takes place. The plum curculio (*Conotrachelus nenuphar* Hbst.) is the most important of these pests, although locally the oriental fruit moth (*Grapholitha molesta* Busck) is sometimes of greater importance. So closely is the curculio associated with peach rot that in former times growers apparently considered the curculio the cause of the rot.

In 1869 Riley (*75, p. 52*) in a report on the curculio stated: "* * * By its punctures it causes the dreaded peach-rot to spread whenever that disease is prevalent * * *." In the process of feeding and laying eggs the curculio makes numerous punctures over the surface of the peach, and these open wounds furnish ideal entry for brown-rot spores. When the beetles are numerous, the infection of these punctures by the brown-rot fungus causes severe damage to the fruit crop if the weather conditions are favorable. This rôle of the curculio in the spread of brown rot is well known and widely recognized. It is not known whether or not this insect inserts spores when it punctures the fruit, but it is certain that a coating of fungicide gives little protection to fruits punctured by the plum curculio.

When a specimen of the plum curculio is examined under suitable magnification, it is found to be ideally equipped as a carrier of brown-rot spores. The segments of the abdomen, the wing elytra, the femora, tibiae, and tarsi are all covered with closely set bristles or bristlelike hairs, and it is very obvious that if one of these insects brushed against spore tufts on the surface of the fruit many spores would adhere to it.

The first step in testing the truth of these deductions consisted in allowing plum-curculio beetles to walk over vigorously sporulating Petri-dish cultures of the brown-rot fungus. The beetles were then examined under a binocular microscope, and numerous brown-rot spores were found adhering to the under surface of the abdomen and to the various segments of the legs. As a further verification, additional beetles were transferred from the brown-rot cultures to sterile agar plates. In due time colonies of the brown-rot fungus developed along the paths in the agar made by the beetles.

In order to make a test under more nearly natural conditions, beetles confined in large battery jars were allowed to feed on rotting peaches for 24-hour periods, after which they were transferred to other jars containing sound peaches. Numerous brown-rot infections developed on these peaches within 24 hours after the transfer of the beetles, and the infections developed in practically all cases at punctures made by them. Jars containing sound peaches to which no beetles were added were maintained as checks, and these peaches remained sound long after the fruit in the jars to which the beetles were added was completely rotted.

A modification of this test consisted in allowing the beetles to feed for 24 hours on rotting fruit and then transferring them for 24 hours to a jar containing nonsprayed peach foliage. The beetles were then transferred to a jar of ripe peaches. Brown rot developed on these peaches within 48 hours, showing that spores still adhered to the beetles after 24 hours feeding on foliage. The checks behaved as in the previous experiment. These experiments were carried out in 1922 and repeated with similar results in 1924.

Although these experiments definitely demonstrate that the plum curculio can serve as a mechanical agent in the dissemination of brown-rot spores, this insect, according to O. I. Snapp, entomologist in the Bureau of Entomology, United States Department of Agriculture, feeds in the field exclusively on sound peaches. Accordingly it seems very probable that the plum curculio is an effective agent in the mechanical dissemination of brown-rot spores only in years that are favorable to the development of the disease when the chances of brushing against spore masses on rotting fruit are numerous. The habit of feeding exclusively on sound tissues largely precludes the possibility of the plum curculio being of much importance as a biological agent in the spread of the disease by eating brown-rot spores and passing them intact through its digestive system.

In experiments conducted jointly by the Bureaus of Entomology and Plant Industry it has been found that in most years about 90 per cent of the brown-rot infections occurring in peach orchards take place through curculio punctures. In those favored sections in which the fruit is free from insect punctures, particularly those of the plum curculio and the oriental fruit moth, brown rot is comparatively unimportant as an orchard disease.

PATHOLOGICAL ANATOMY

FLORAL PARTS

The mycelium of the brown-rot fungus is intercellular in the petals and sepals of the peach blossom. In both these organs the cells are so loosely arranged and the intercellular spaces so numerous that the mycelium spreads rapidly through the entire organs. Sections prepared from the style and stigma of artificially inoculated peach blossoms show that the conidia germinate (pl. 7, A) on the surface of the stigma and that the germ tubes grow down intercellularly among the loosely arranged cells of the style in much the same manner as the pollen tubes. All the parenchymatous tissues of the ovary may be invaded. (Pl. 7, B and C.) The mycelium was observed in the spaces between the pollen grains in mature anthers. Conidia may be produced on the surface of all floral parts.

FRUITS

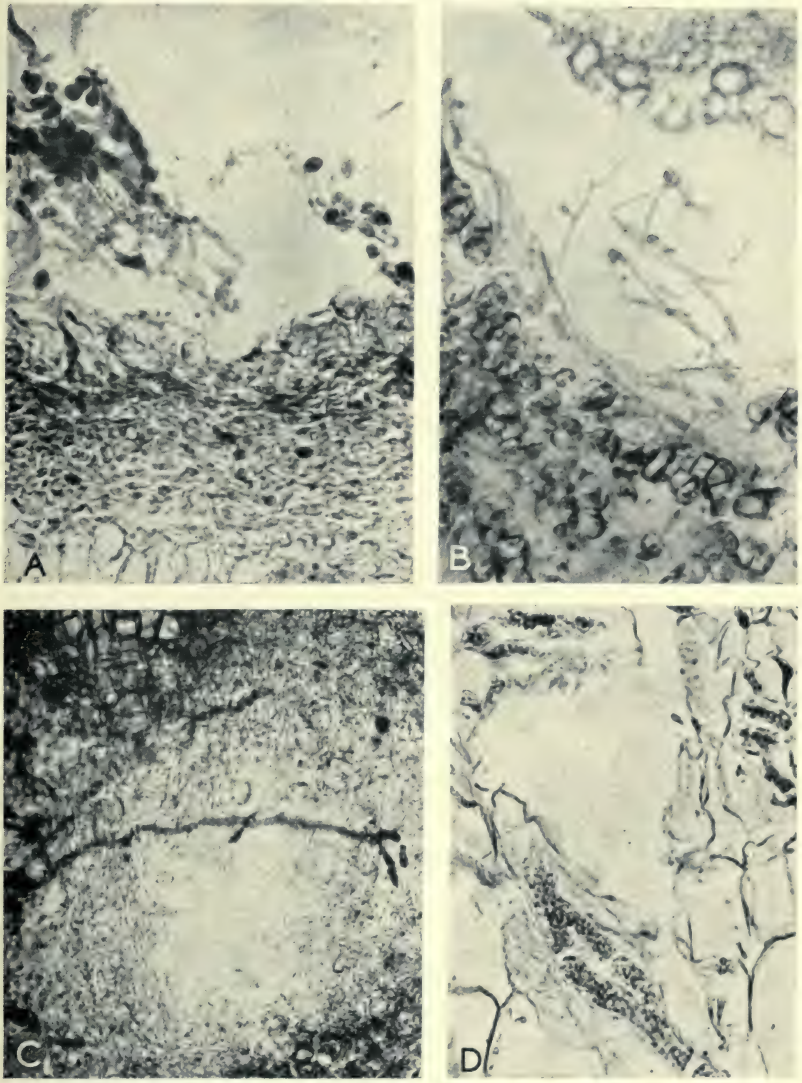
In peach fruits the fungus is intercellular. (Pl. 7, D.) It dissolves the middle lamella and by occupying much of the space thus formed separates the cells of the invaded part of the peach from one another. Galloway (*39*) found the mycelium intercellular but states that in some cases it seemed to have penetrated the cell walls. Cooley (*20*) stated that hyphae penetrate the cells of the plum at any point of contact, but Valleau (*97*) observed that in the tissues of plum and apple the hyphae are entirely intercellular. Valleau also observed that the middle lamella is dissolved slightly in advance of the penetration of the hyphae. He considers that the absence of the middle lamella in the tissues of ripe fruits explains the rapidity with which rot develops in them.

TWIGS

In 1891 Smith (*92*) presented a brief account of the histology of peach-twig cankers caused by the brown-rot fungus, but since that time, so far as the writers are aware, no detailed histological work has been done. It is true that Jehle (*48*), Fant (*37*), and Cook (*19*) have discussed the cankers at some length, but their interest in them was mainly from an etiologic viewpoint.

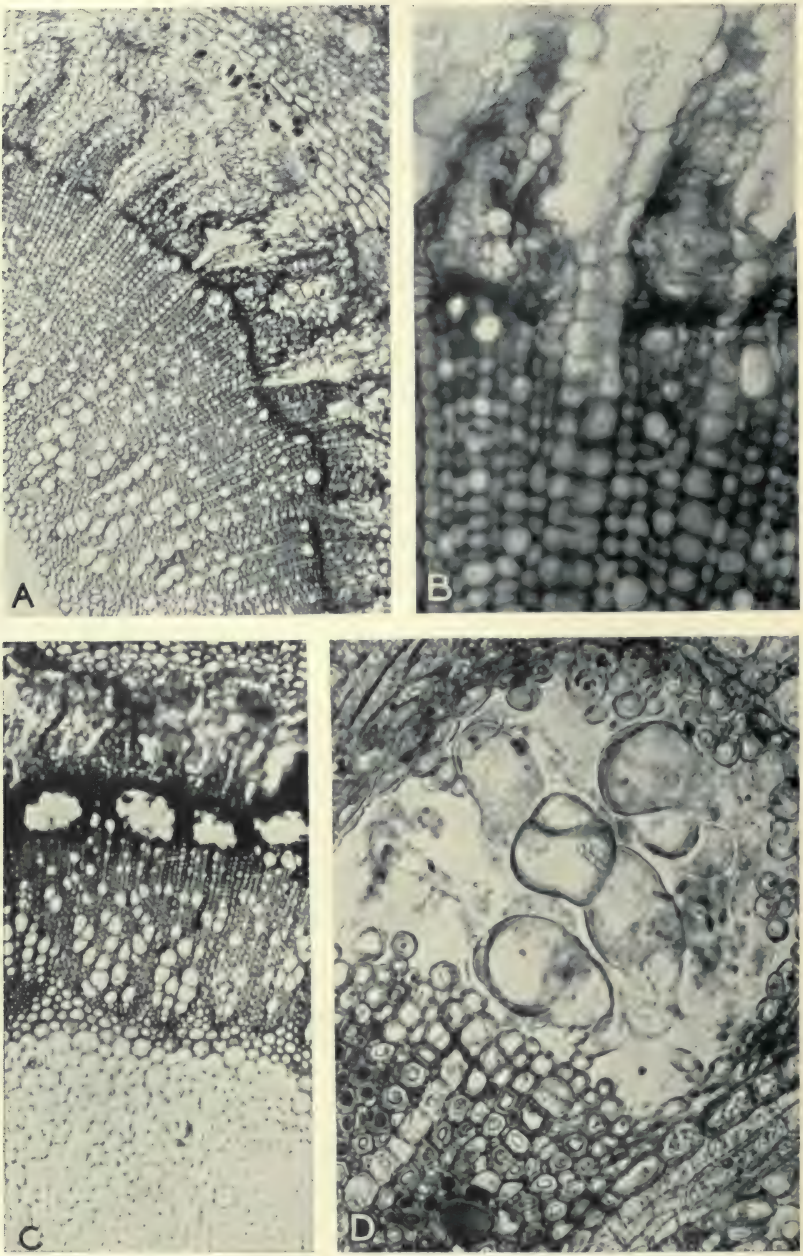
Twigs with blighted blossoms and cankers resulting from blossom infections were collected from trees of the varieties Hiley and Uneeda at various times during the years 1927 and 1928. Sections were prepared from these twigs by means of a sliding microtome. Some of the sections were stained with safranin and light green, and others were mounted unstained. In the first sections examined the fungus was growing through the peduncle but had not reached the tissues of the twig, and the only symptom present was a crescent-shaped discolored region on one side of the peduncle.

The first symptom of canker formation in the tissues of the twig is the presence of a discontinuous narrow brown zone in the region of the cambium. (Pl. 8, A.) The cells in this region are dark colored, and the walls have collapsed. The discolored zone is discontinuous because the cells of the larger pith rays are not affected. This is clearly illustrated in Plate 8, B. The mycelium of the fungus has not been observed in the tissues of very young cankers,



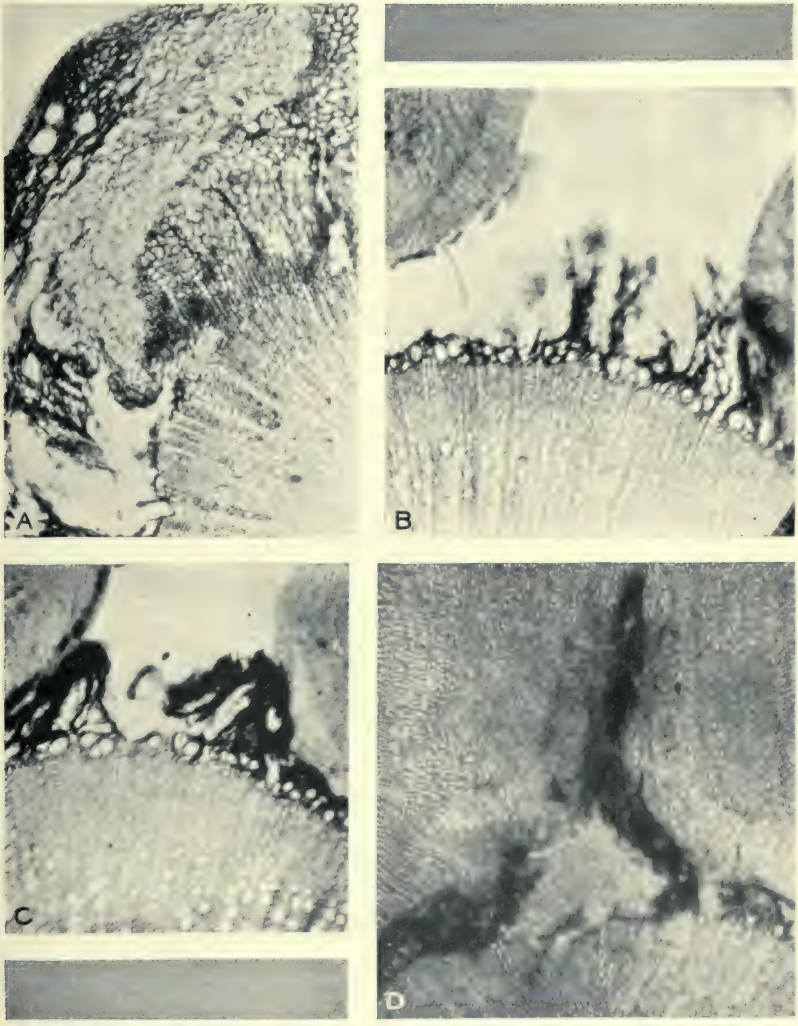
BLOSSOM BLIGHT OF THE PEACH CAUSED BY SCLEROTINIA FRUCTICOLA

A, Conidia germinating on the surface of stigma of Uneeda peach blossom; B, mycelium in space between ovary wall and young ovule of infected peach blossom; C, mycelium penetrating tissues of the young ovule; D, mycelium in tissue of mature Yellow Hiley peach. All × 340.



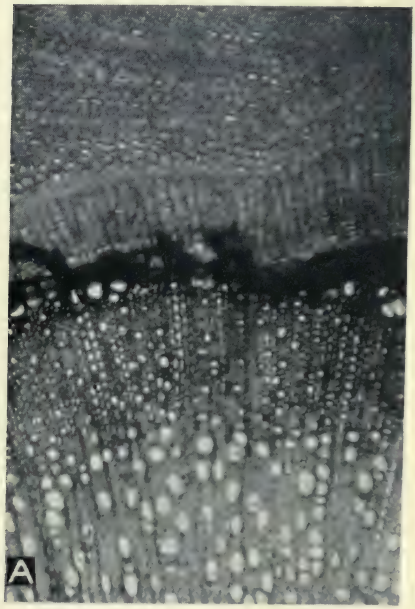
PEACH TWIG CANKERS CAUSED BY SCLEROTINIA FRUCTICOLA

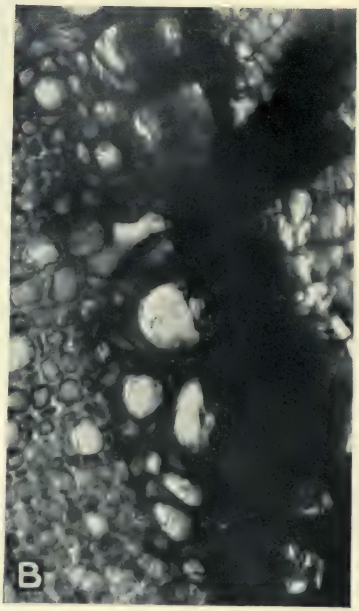
A, Early stage in formation of twig cankers. The discontinuous dark line in the region of the cambium is one of the first symptoms. × 80. B, Similar to A but at higher magnification to show more clearly the collapse of the tissue in the region of the cambium. × 340. C, The gum-pocket stage in the formation of the twig cankers. × 80. D, Gum pocket at higher magnification. × 340.

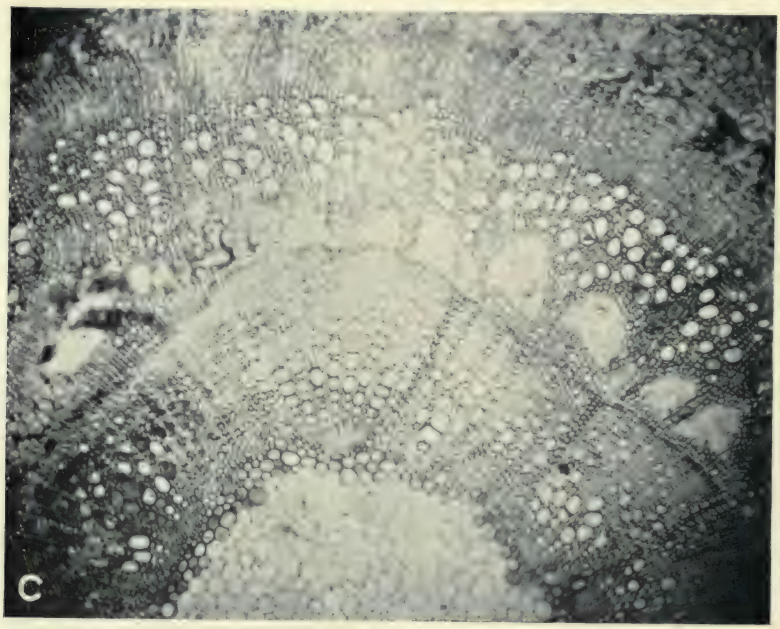


PEACH TWIG CANKERS CAUSED BY SCLEROTINIA FRUCTICOLA

A, Formation of a wound periderm extending from the epidermis to the cambium at some distance from the necrotic region; B, callus tissue rolling in over necrotic region; C, callus tissue from the two sides almost united; D, callus tissue united, leaving a small triangular-shaped gap at the center of the necrotic region. All × 60.







PEACH TWIG CANKERS CAUSED BY SCLEROTINIA FRUCTICOLA

A, Callus and necrotic tissue. The callus tissue does not unite with tissue of the necrotic region but is merely superimposed on it. × 80. B, Portion of A at higher magnification. The dark zone is the crushed fragments of the necrotic tissue. × 340. C, Uneeda twig collected and sectioned May 19, 1927, showing new tissue formed external to gum pockets which developed as the result of blossom blight in March, 1927. × 80.

and it is not known whether the discoloration and collapse of the cells in the region of the cambium is caused by actual penetration of the cells by the hyphae of the fungus or by enzymes liberated by the fungus. These early symptoms pass very soon into a condition in which there is a circle of gum pockets (pl. 8, C) in the region formerly occupied by the discolored zone. It is very evident that these gum pockets are merely the aftermath of the killing of the cells. While the gum pockets may at times form a band encircling the xylem, they remain as distinct entities because the cells of the larger pith rays are not affected. (Pl. 8, C.) Smith (*92, p. 38*) has described the conditions of the tissue at this period in the development of the cankers as follows:

> The cambium and soft bast cylinders had disappeared almost completely with the formation of extensive gum pockets. These pockets were full of the active mycelium of *Monilia*. This also penetrated into the cortical parenchyma to some extent, and to a lesser degree into the xylem. Practically speaking, the wood and the pith and all the cylinders external to the soft bast were intact. On unmagnified cross sections a zone of discoloration was visible below the wood and the bark. On magnification this was found to consist * * * of a gum cavity containing mycelium and fragments of tissue and bordered by irregular dark zones, the one within composed of young wood and vessels laid down this spring, and the one without composed of remnants of soft bast and phlœm rays. The bundles of fibers were also changed from a glistening white to a dirty yellowish brown.

Smith apparently found the mycelium of the fungus in the cortical parenchyma. The writers have not been so fortunate, but there can be no doubt that the cells in this region are seriously affected. There is no pronounced dissolution of the cell walls with formation of gum pockets, but instead the cells lose their turgidity, and the walls, instead of being practically hyaline, are brown and are swollen to almost twice their normal thickness.

The formation of the extensive gum pockets in the region of the cambium and the destruction of the cortical parenchyma are the final episode in the histological changes produced directly by the fungus. The subsequent changes are associated with the development of callus tissue to cover the necrotic region of the twig. A wound periderm is initiated at each side of the necrotic region and extends as a sloping, irregular band from the region of the cambium to the epidermis. (Pl. 9, A.) This periderm is initiated not at the apparent boundary between the mass of necrotic, disrupted cells and the healthy tissues, but at some distance from this boundary in apparently healthy tissues. Microchemical tests to detect a suberization of cells preceding the initiation of a wound periderm gave negative results. The tests, however, were too few to warrant drawing a definite conclusion on this point.

The regeneration of the tissues of the twig presents no striking novelties and is well described by the following generalized description of the process taken from Strasburger (*94, p. 164*):

> In stems of Gymnosperms and Dicotyledons, wounds which extend into the wood become surrounded and finally overcapped by an outgrowth of tissue arising from the exposed cambium. While the callus tissue is still in process of gradually growing over the wounded surface, an outer protective covering of cork is developed; at the same time a new cambium is formed within the callus by the differentiation of an inner layer of cells, continuous with the cambium of the stem. When the margins of the over-growing callus tissue ultimately meet and close together over the wound, the edges of its cambium unite and

form a complete cambial layer, continuing the cambium of the stem over the surface of the wound. The wood formed by this new cambium never coalesces with the old wood which is brown and dead.

The various stages in the overcapping of the necrotic region are illustrated in Plate 9, B, C, and D, and Plate 10, A and B.

The histological changes come to an end when the cambium of the two layers of the callus tissues, which have been gradually approaching each other, unite. This fusion of the cambium is followed by the production of normal rings of wood, and usually by the end of the second season after the initiation of the canker it is impossible to tell from the appearance of the twig surface that a canker had been present.

Earlier in the discussion it was stated that a ring of gum pockets may encircle the xylem. These gum pockets persist in the tissues but cease to enlarge, and new tissues are laid down exterior to them. (Pl. 10, C.) The cambium that initiates the new tissues probably originates by a lateral division of the uninjured cambial cells capping the pith rays.

CONTROL OF PEACH BROWN ROT

SANITARY MEASURES

The removal of mummied fruits, blighted twigs, and all other parts infected by the fungus was recommended by early investigators as the sole means of control of peach brown rot. Later, with the development of spraying, orchard sanitation was recommended only as a supplementary control measure. Smith (*91*) advocated the removal of rotting fruits as soon as they appear in the orchards and before spores are formed on them. He insisted, however, that to be successful it must be a community affair, since one neglected orchard may furnish spores enough to reinfect all the surrounding orchards. Quaintance (*70*) suggested, in addition to removal of mummies and rotted fruits, the pruning out of blighted spurs and twigs.

Jehle (*48*) recommended the removal of mummies early enough to prevent the growth of the fungus through the stem of the mummy and into the twig. He also recommended the removal of cankers. McClintock (*52*) suggested that cankers be pruned out just after harvest so that the cankered twigs may be removed from the orchard along with the rotten fruit collected from the trees and from the ground. Pollock (*68*) considered the plowing under of mummies a doubtful help in control, because he found that the sclerotia from which apothecia arise could live in the soil for at least 10 years. On the other hand, McCubbin (*54*), Archibald (*4*), and Brooks and Fisher (*16*) found that plowing greatly reduced apothecial production, and they considered it as helpful in control. Ezekiel (*33*), as the result of laboratory experiments, suggested that liming the soil might be helpful in the prevention of apothecial production, but he did not make orchard tests with lime. Later (*36*) he found that mummies disintegrate very rapidly when buried in the soil, and accordingly he recommended fall plowing. He also recommended a loosening of the soil by cultivation during the pink-bud stage of the peach in early spring, since mummies disturbed at that time rarely produce apothecia.

It is certain that sanitary measures alone will not control any phase of brown rot, and it is difficult to estimate the benefits of orchard sanitation. Removal of mummies, however, undoubtedly has some value in the control of brown rot in its various phases. As stated by Smith (*90*), to be effective, removal of mummies should be a community affair, because the conidia may be easily borne by the wind from a neglected orchard to one in which all sources of infection have been removed in so far as practicable. It is the dissemination of conidia by the wind that prevents experimentation on the effectiveness of this method of control. One might consider that the removal, in so far as practicable, of all infection sources in one half of an orchard, leaving the other half as a check, should result in less brown rot in the one half than in the other, but it would be found that sufficient conidia had been blown into the cleaned half to start numerous initial infections which would soon become new infection centers.

The removal of newly infected blossoms, leaves, and twigs is quite impracticable, as is also the removal before conidia are formed of newly infected fruits except in small plantings. Frequently growers instruct pickers to collect all rotted and mummied fruits along with the sound, thus enormously increasing the chance of infection by increasing the number of conidia on the surface of the fruit. Collection of the rotted fruits is made for the purpose of removing from the orchard possible sources of infection for the following year, but it should not be done at the time when the sound fruits are gathered. It is, however, both practicable and helpful to remove rotten fruits directly after picking the crop, to prevent twig infection and canker formation, besides reducing the number of prospective mummies. Removal of rotten fruits from trees of early varieties also helps somewhat in the protection of later varieties by reducing the number of infection sources.

The brown-rot fungus attacks many species of wild plum, and all the different phases of the disease described for the peach, viz, blossom blight, twig cankers, fruit rot, and mummy formation, may be observed on these wild hosts. The writers have observed apothecia produced in abundance under trees in thickets such as that illustrated in Plate 4, B. When blossom blight develops in these thickets, with the production of myriads of conidia on the blighted blossoms, it is only too evident that wild plum trees serve as a fertile source of infectious material, both ascospores and conidia, that may be blown to near-by commercial orchards. Since the disease runs its course unchecked on these wild hosts, it is also evident that dangerous centers of infection may exist year after year. Spores blown from these wild plums may initiate brown rot in peach orchards previously free from the disease.

The writers realize the impossibility of completely eliminating wild plums and wild-peach seedlings from any given district, but in sections devoted largely to peach production it is unwise to allow plum and wild-peach seedling thickets like that shown in Plate 4, B, to develop near commercial orchards. Here again the problem is one of concerted community action; and if all the growers cut down the trees on their own property at regular intervals, much of the danger of brown rot from wild plum and peach seedlings is eliminated.

Failing in community action, the individual growers should at least cut down all such trees along fence rows and at the edges of fields bordering their orchards.

Information on orchard sanitation as a supplementary control of brown rot may be summarized as follows:

To be most effective it should be a community affair.

Mummies hanging on the trees should be removed from the orchard as soon as possible after the crop has been harvested.

Mummies on the ground should be plowed under or otherwise disposed of in the fall or in the spring before the blossoms open.

Cankers and dead twigs should be removed at pruning time for the good of the trees, but their removal probably is of little help in controlling the disease.

Wild-plum trees and peach seedlings near peach orchards should be cut down at regular intervals, and if possible thickets of wild-plum trees and peach seedlings should not be allowed to develop in sections devoted to peach culture.

SPRAYING AND DUSTING

Certain sprays or dusts applied during the growing season control the brown-rot disease to a greater or lesser extent, depending on the season. All other methods of control are supplementary to spraying or dusting and are useful only in that they make control by spraying or dusting more nearly complete or more readily accomplished. During at least a part of the season the fungicidal sprays or dusts should be combined with an insecticide for the control of the plum curculio. As previously stated, the control of the curculio is important in the control of brown rot, because, except in years particularly favorable to the development of the rot, about 90 per cent of the brown-rot infections in the orchard take place through curculio punctures.

Sprays applied during the dormant season, even those many times stronger than the lethal dosage for brown-rot spores, have no noticeable effect in controlling the disease. Manns and Adams (*55*) found that from cankers on dormant peach twigs that had been dipped in strong Bordeaux mixture and dried for 24 hours the fungus pushed out through the fungicide and produced abundant conidia.

Fungicides such as Bordeaux mixture, potassium sulphide, and flowers of sulphur had been recommended at times for use on the peach, but it was not until 1907, when Scott (*86*) introduced a mixture of sulphur, freshly slaked quicklime, and water, which he called self-boiled lime-sulphur, that spraying for the control of brown rot became practical and effective. The fungicides previously recommended either injured the trees severely or did not control the disease. Bordeaux mixture, which at one time had been generally recommended, was abandoned because even with the minimum content of copper necessary for the control of brown rot it frequently injured the foliage of the peach severely and caused defoliation in the early summer. Scott's mixture controlled the disease without causing serious injury to foliage or other parts of the tree. Scott, after considerable experimentation in orchards, finally decided that the self-boiled lime-sulphur gave best results when it was composed of 8 pounds of sulphur and 8 pounds of stone lime to 50 gallons of water. At this strength scab and brown rot were controlled, and arsenate of lead could be added to the mixture without danger of

serious injury to the peach. The heat from the slaking of this quantity of lime was effective in forming an intimate mixture of sulphur and milk of lime, which remained in suspension for some time. The sprays now most commonly used are essentially the same as Scott's mixture of sulphur and lime except that these ingredients are brought into suspension by the action of a colloid such as casein or glue instead of heat.[11]

With the development of a finely powdered sulphur, about 1912, and efficient machinery for its application, dusting for the control of brown rot has yielded good results and is widely used. Sulphur in this form is mixed with hydrated lime and powdered arsenate of lead to form a mixture which is effective against brown rot, scab, and curculio, and causes little injury to the peach.

Discussion of the effectiveness of spraying and dusting with fungicides in the control of brown rot will be divided into two parts: (1) Effectiveness in the prevention of blossom blight and resulting twig cankers; (2) effectiveness in the prevention of fruit rot and incidentally of twig and limb infections resulting from fruit rot.

CONTROL OF BLOSSOM BLIGHT

An application of a fungicide just before the blossoms open has long been recommended for the control of the brown-rot blossom blight of stone fruits. Galloway (*39*) recommended it for the control of cherry-blossom blight and Chester (*17*) for the control of peach-blossom blight. Cory (*22*) in Maryland, Berkeley (*11*) in Canada, and Jehle (*48*) in New York have reported good results from applications made before the peach blossoms open, i. e., when the pink color of the petals is visible in the still unopen buds. Cunningham (*24*) in New Zealand recommends two preblossom applications, the first when the buds begin to swell and the second when the pink of the petals is first visible. Brooks and Fisher (*16*) in Washington and Oregon reduced the number of blossom infections of prunes and cherries by a preblossom application, but usually the application did not result in an increase in the crop of fruit.

Rudolph (*82*) in California found that in severe cases of apricot-blossom blight caused by *Sclerotinia cinerea*[12] it was necessary to spray the open blossoms as well as the blossom buds with Bordeaux mixture to obtain control. Tesche (*95*) reports reduction of the apricot-blossom blight by two preblossom applications of Bordeaux mixture to which oil had been added as a spreader. Robertson (*81*) in British Columbia did not control cherry-blossom blight, caused presumably by *S. cinerea* (*Monilia oregonensis*), with an application of Bordeaux mixture in April following a pruning out of useless wood and dead-fruit spurs.

Rice (*74*) in New Zealand reports no effective control of peach-blossom blight by spraying, and McClintock (*52*) in Georgia found that an application of strong lime-sulphur solution applied when the buds were swelling was of little value in the control of blossom blight of Early Wheeler (*Red Bird*) peaches.

---

[11] For specific directions for making self-boiled lime-sulphur and its substitutes see Farmers' Bul. 1527 (*80*).

[12] It is commonly accepted that this fungus is present on the Pacific coast, although the apothecial stage has never been observed.

In the years 1922 to 1924, inclusive, the writers performed experiments designed to test the effectiveness of preblossom spraying in the control of brown-rot blossom blight in central Georgia. In that section blossom blight is normally prevalent only on early varieties, although in seasons particularly favorable to its development it may be found to a slight extent on all varieties. Even with the more susceptible early varieties it is only in certain seasons that control measures are needed. Spray experiments were conducted over a period of three years, but no satisfactory results were obtained. In the orchards used there were abundant mummies producing conidia and ascospores, so that there was no lack of infectious material.

The selection of the proper time for applying the spray is an important problem in spraying for the control of blossom blight. Since, as previously shown, all parts of the blossoms are susceptible, it was thought that a spray applied to open blossoms would be effective. It was found, however, that it was not possible to find all the blossoms on all the trees open at anything like the same time. In 1922 only one-half the blossoms were open when the sprays were applied. In 1923 the time of application was delayed; but even when 20 per cent of the blossoms had dropped their petals, 13 per cent were not yet showing pink. In 1924, with an even greater delay, 8 per cent were in a stage too small to be protected. The only solution of the timing problem would be two or three applications during the blossoming period, which would be so expensive as to be prohibitive. Various materials have been used, but lime-sulphur solution (33° Baumé) diluted at the rate of 2 gallons to 50 gallons of water has given the best results. In 1924 when the sprays were applied late in the blossoming period the dilute lime-sulphur solution caused slight injury to the blossoms, and it is quite possible that two or three applications would cause severe injury. Some of the colloidal sulphur sprays could probably be used with safety, but they would not adhere so well as lime-sulphur solution. Self-boiled lime sulphur with and without casein lime was less effective than lime-sulphur solution, and a dust composed of finely ground sulphur, 85 per cent, and hydrated lime, 15 per cent, was wholly ineffective.

CONTROL OF FRUIT ROT

Scott (*86*) not only worked out a safe fungicide for use on the peach in the growing season but also, in cooperation with Quaintance, of the Bureau of Entomology, worked out a combined spraying schedule for the control of the curculio, scab, and brown rot. For varieties approximating the season of the Elberta variety this schedule was as follows:

First application.—When the calyces or "shucks" are shed, which is usually about 10 days after the petals have fallen, spray with a suspension of arsenate of lead and milk of lime in water for the control of the curculio.

Second application.—Two weeks after the first application, or about four weeks after the petals have fallen, spray with self-boiled lime-sulphur to which arsenate of lead is added. This application is primarily for the control of curculio and scab.

Third application.—About one month before the fruit ripens, spray with self-boiled lime-sulphur for the control of brown rot.

Scott found after long experimentation that earlier treatments with self-boiled lime-sulphur were unnecessary. He and Ayres (*87*)

also found that the sprayed fruit was less liable to rot in transit and on the market than the unsprayed. At the present time many investigators advise earlier applications for the control of brown rot, but such applications are of doubtful usefulness.

After the introduction of finely ground dusting sulphur about 1912 the use of this substance for the control of brown rot began, and it is now extensively used for that purpose. It has the advantage of being easily and quickly applied; and applications can be made shortly before harvest, when the fruit is reaching the stage of greatest susceptibility to the disease, without the staining of fruit, which often results from applications of spray made at that time.

The spray or dust schedule recommended for general use at the present time follows closely the original schedule devised by Scott and is as follows:

First application.—When calyces or "shucks" are shedding, which is usually about 10 days after the falling of the petals—

Spray: Powdered arsenate of lead,[13] 1 pound (or 2 pounds of the paste), and the milk of lime from 3 pounds of stone lime or 4 pounds of hydrated lime, with water sufficient to make 50 gallons; or

Dust: (1) Hydrated lime, 95 per cent; arsenate of lead, 5 per cent; or (2) sulphur, 80 per cent; arsenate of lead, 5 per cent; hydrated lime, 15 per cent.

Second application.—Two weeks after the first application, or about four weeks after the petals have fallen—

Spray: Self-boiled lime-sulphur 8–8–50 (or substitute), to each 50 gallons of which 1 pound of powdered arsenate of lead (or 2 pounds of the paste) is added; or

Dust: Sulphur, 80 per cent; arsenate of lead, 5 per cent; hydrated lime, 15 per cent.

Third application.—One month before each variety is expected to ripen—

Spray: Self-boiled lime-sulphur 8–8–50 (or substitute) without the addition of arsenate of lead; or

Dust: (1) Sulphur, 80 per cent; hydrated lime, 20 per cent; or (2) sulphur, 80 per cent; arsenate of lead, 5 per cent; hydrated lime, 15 per cent.

For the southeastern part of the United States, including Georgia and the Gulf States, the following schedule is recommended:

First application.—Immediately after 75 per cent of the petals have fallen—

Spray: Powdered arsenate of lead, 1 pound (or 2 pounds of the paste), and the milk of lime from 3 pounds of stone lime or 4 pounds of hydrated lime with water sufficient to make 50 gallons; or

Dust: (1) Hydrated lime, 95 per cent; arsenate of lead, 5 per cent; or (2) sulphur, 80 per cent; arsenate of lead, 5 per cent; hydrated lime, 15 per cent.

Second application.—When calyces or shucks are shedding, which is usually about 10 days after the falling of the petals—

Spray: Same as for first application; or

Dust: Same as for first application.

Third application.—Two weeks after the second application, or about four weeks after the first application—

Spray: Self-boiled lime-sulphur 8–8–50 (or substitute); or

Dust: (1) Sulphur, 80 per cent; hydrated lime, 20 per cent; or (2) sulphur, 80 per cent; arsenate of lead, 5 per cent; hydrated lime, 15 per cent.

Fourth application.—One month before each variety is expected to ripen—

Spray: Self-boiled lime-sulphur 8–8–50 (or substitute), to each 50 gallons of which 1 pound of powdered arsenate of lead (or 2 pounds of the paste) is added; or

Dust: Sulphur, 80 per cent; arsenate of lead, 5 per cent; hydrated lime, 15 per cent.[14]

---

[13] Directions for the use of arsenate of lead in the control of the curculio were furnished by the Bureau of Entomology, U. S. Department of Agriculture.

[14] For a more complete discussion of spray schedules, specific directions for making self-boiled lime-sulphur and substitutes for it, and dust formulas, the reader is referred to Farmers' Bulletin 1527 (*80*) and Farmers' Bulletin 1557 (*93*).

FUMIGATION

The lethal effects of the vapors of certain substances on bacteria, fungi, insects, and other forms of life are well known. Their employment as antiseptics, disinfectants, germicides, and insecticides has been a common practice for many years. It is not surprising, therefore, to find a large volume of literature dealing with the subject. A review of the literature dealing only with the more important contributions to the subject would far exceed the limits of this bulletin. It is sufficient to say that the experiments herein reported represent an attempt to determine the possibility of a successful specific application of the well-known principles of fumigation.

As a result of the accidental discovery that *Sclerotinia fructicola* is particularly susceptible to vapors given off by ethyl alcohol, these experiments were begun with the hope that a substance might be found whose vapors would be of practical use in the killing of brown-rot spores and hyphae on peaches and other stone fruits either in closed compartments at packing houses or in refrigerator cars during transit. For many years it has been the custom of the senior writer after transferring fungus cultures from one tube to another to moisten the lower portion of the cotton plug above the new culture with a mixture of chemicals[15] used for the killing of mites. In the writer's experience this mixture had never affected in any noticeable way the growth of the new culture, but in the case of the brown-rot organism culture transfers from 18 different sources all failed to grow. By testing the ingredients of the mixture separately it was found that alcohol was the only one that prevented growth; and since only the vapor of this substance could reach the fungus, it was assumed that it was responsible for the failure of the transferred conidia and hyphae to develop. Of the other ingredients mercuric chloride is well known to be toxic to fungi when in contact with them, but it does not vaporize sufficiently, at least, to be toxic to the brown-rot fungus when a solution of it is applied to the culture-tube plug. The two remaining ingredients, arsenate of lead and glycerin, when applied to culture-tube plugs had no effect on growth.

The choice of substances for use in the experiments followed no general rules. Some of the essential oils, such as oil of thyme, oil of eucalyptus, and oil of peppermint, were chosen because of their well-known antiseptic and germicidal properties. Others were used at the suggestion of G. A. Russell, then of the office of Drug Plant Investigations, Bureau of Plant Industry. Benzaldehyde was used on account of the toxicity of aldehydes for plant growth and because of its cheapness. Copper sulphate was used to ascertain whether or not it had fungicidal powers when not in contact with conidia or hyphae. Mercury and aniline are too toxic to man to be very promising. The former received a trial because Larson (*51*) had found it to be toxic to the larvae and eggs of the bean weevil when in the same jar but not in contact with them. Aniline, acetic acid, carbon tetrachloride, furfural, and several other chemicals were tried because it was considered desirable to try readily obtainable substances

[15] Formula: Alcohol, 95 ml; glycerin, 50 ml; bichloride of mercury, 2 g[16]; arsenate of lead, 1 g.

[16] g (instead of gm.) is the abbreviation recently adopted by the Government Printing Office for gram or grams.

of different chemical composition. Tricresol and toluene were tried only because they are well-known germicides. Chloral hydrate was chosen because of its narcotic properties. Paradichlorobenzene was introduced by Blakeslee (*12*) for the control of the peach borer and has come into general use for that purpose. The toxicity of acetic acid suggested the use of certain acetates even though they are relatively nonvolatile. Certain commonly used fumigants, such as sulphur dioxide and formaldehyde, were not used, for the reason that they were known to be injurious to peach fruits.

Preliminary experiments to eliminate from further tests those liquid substances that did not prevent growth were made by moistening with 1 to 2 ml of each substance the lower ends of the cotton plugs of culture tubes to which the fungus had been newly transferred. Checks were held in all cases. The following substances entirely prevented growth:

Acetic acid, glacial; alcohol, 95 per cent; aniline; benzaldehyde; carbon tetrachloride; cassia oil; chloral hydrate, saturated aqueous solution; *Eucalyptus globulus* oil; eugenol; horsemint (*Monarda punctata*) oil; lemon oil, pressed; peppermint (*Mentha piperita*) oil; safrol; sassafras oil, artificial; sassafras oil, natural; thyme oil, light; toluene; tricresol; wormseed oil.

The following substances did not prevent growth:

Cedar oil, light; clove oil; copper sulphate, saturated aqueous solution; lead arsenate, 1 g in water 100 ml; mercuric chloride, saturated aqueous solution; sodium salicylate, M/1 aqueous solution.

A crystal of copper sulphate ($CuSO_4 \cdot 5H_2O$) placed in a culture tube at the foot of the agar slant did not hinder growth until, slowly dissolving, it permeated the culture medium and finally came into actual contact with the fungus. Mercury, 0.3 ml, at the foot of agar slants, entirely prevented growth.

To determine whether or not growth in cultures could be stopped after a vigorous beginning, 1 to 2 ml of the following substances were dropped on the lower ends of plugs of culture tubes containing 2-day-old growths of the fungus measuring approximately 1 cm across: Benzaldehyde; lemon oil, distilled; horsemint oil; thyme oil, light. Five days later the slants of the untreated tubes that were held as checks were entirely covered by the fungus, while there was no further growth in the treated tubes. Cultures from the latter tubes showed the fungus to be dead.

In some of the experiments on the effects of exposing conidia to vapors the substance under trial was placed in the bottom of the cavity of a hang-drop slide and the spores were exposed in a hanging drop on the under surface of a cover glass placed over the cavity. After the time allowed for exposure had elapsed the cover glass with its drop containing the conidia was removed and placed on a similar slide containing only water, and later examined for germination. This method was abandoned, for the reason that the exposure of conidia in water was not as they would be exposed in practical usage, and because some of the vapors would probably be carried over in the hanging drop when the change to a different slide was made.

The results obtained by this method, however, agreed very well with those obtained by the following method, which was finally adopted as a standard. The fungus was grown on 4 per cent potato

agar; and when conidia production became profuse, bits of the medium covered with conidia were removed and placed on ordinary microscopic slides. These slides were then placed under inverted battery jars the sides of which had been sprayed with the substance (liquid) to be tested. Solid or dry substances were scattered about under the battery jar one and one-half hours before the beginning of the tests. After the time chosen for exposure had elapsed the conidia were exposed to the air of the room for a few minutes and then tested for germination in hanging drops of either distilled water or sterile prune juice, the latter giving the more uniform results. Checks were held in all cases; and unless the percentage of germination of the nontreated conidia was at least 50, the results were not considered. Usually the percentage was above 90. Since trials showed that conidia not germinating in 24 hours did not germinate at all, results were regularly taken after 24 hours. The results of these experiments are recorded in Table 6.

TABLE 6.—*Results of exposure of conidia of Sclerotinia fructicola to vapors of various substances*

Material	Conidia germinating in 24 hours after exposure for [1]—						
	¼ hour	½ hour	1 hour	2 hours	3 hours	4 hours	5 hours
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Acetal		0–55	0–95	0–95			
Acetic acid, glacial	0–50	0–98		0–95			
Acetophenone		0–55	0–95	0–95			
Alcohol, ethyl		100–98		25–95	0–50		
m-Aminobenzoic acid			80–95	95–98		90–98	
Aniline		1–90	1–90	0–90	0–90		
Barium acetate			85–95	98–98		75–98	
Benzaldehyde	0–99	0–99	0–98	0–80			
Benzaldehyde, 0.3 ml; in water, 100 ml			1–80	5–80			
Benzaldehyde, 3 ml; in water, 100 ml	10–50	0–50					
Benzyl acetate			0–98	0–98	0–98		
Benzyl alcohol			0. 01–98	0–98	0–98		
Calcium acetate			75–95	95–95		98–98	
Carbon tetrachloride			90–98	95–80			
p-Dichlorobenzene			0–95	0–95			
Ethyl salicylate			0. 05–100	0–100	0–100	0–100	
Ethylene chlorohydrin	100–98	50–98	30–98	0–95		0–90	
Ethylene dichloride	100–98	50–98	50–100	0–95		0–90	
Eugenol		90–99	65–99				
Formamide			0–85	0–85	0–85	0–85	
Furfural		0. 05–85	0–85	0–85	0–85		
Isopropanol	90–98	0–98	0. 003–98	0–95		0–90	
Mercury				8–90	25–90		2–50
Methyl acetate		5–100	0–100	0–100	0–100	0–100	
Methyl salicylate			3–100	0–100	0–100	0–100	
o-Nitrophenol			1–95	0–95			
p-Nitrophenol			80–95	98–98		100–98	
Oil of apricot kernels			50–65	65–65	50–65		
Oil of cassia			0. 5–50	0–99			
Oil of cloves		92–99	95–99				
Oil of cedar, light			75–80		65–85		0. 2–75
Oil of *Eucalyptus globulus*		4–85	0–80				
Oil of lemon		25–90	10–95	5–95	0. 1–90		
Oil of lemon, distilled				6–75	0. 5–75	2–60	0–75
Oil of lemon, pressed				2–75	0. 1–75	0–68	
Oil of *Monarda punctata*	3–90	0. 4–90	0–99	0–99			
Oil of peppermint			7–95	0. 3–94	0–50		
Oil of sassafras, natural			1–80	0. 5–85	0–75		
Oil of sassafras, artificial			0–80	0–75			
Oil of thyme	0–90	0. 5–90	0–90	0–90			
Oil of American wormseed			0. 4–80	0–75			
Phloroglucinol				100–98		100–98	
Resorcinol				100–98		98–98	
Safrol			2–80	4–85	0–75		
Salicylaldehyde		0–55	0–95	0–95			

[1] The first number in each column denotes the percentage of treated and the second number the percentage of control (nontreated) conidia germinating.

Trials with fruits were disappointing because all substances that were toxic to the conidia of the fungus imparted to the fruit a flavor and an odor that lessened or destroyed its market value. Many substances such as acetic acid blackened the fruit in a few minutes, and most of them injured it to some extent. These injuries masked the results in rot control, but apparently the rot was checked.

The problem of finding a successful fumigant is a difficult one. It is necessary that the fumigant be toxic to the fungus, noninjurious to peaches, odorless, tasteless, noninflammable, nontoxic to man, and relatively cheap.

SUMMARY

The history of the brown-rot disease in the United States reveals that while the disease was not recognized generally as such until after 1880, it had been reported at least a century ago. Its fungous origin was clearly understood by a number of early investigators.

In the more humid sections of the United States the disease takes a heavy toll, amounting, in years favorable to its development, to as much as $5,000,000. Some fruit is lost every year, and losses occur while the fruit is in the orchard, in transit, in the markets, and in the possession of the consumer.

Practically all the commercial varieties of the peach show some resistance to brown rot, but it is impossible to evaluate this resistance definitely on account of differences in periods of ripening under varying environmental conditions. The early maturing varieties seem to be more susceptible to blossom blight than those ripening later, but here again it is difficult to eliminate the environmental factor and make an adequate comparison of varietal resistance. It is true, however, that the present-day varieties are more resistant than the older and often better-flavored varieties and have supplanted them largely for this reason.

The taxonomic position of the common brown-rot fungus is reviewed in detail, and the writers reaffirm their previous position that the name *Sclerotinia fructicola* (Wint.) Rehm is the name that should be applied to the fungus.

Sclerotinia fructicola occurs in the United States, Canada, Australia, and New Zealand.

The morphology of the fungus is described, and details of the structure and characters of the apothecia, asci, paraphyses, ascospores, conidia, microconidia, and germ tubes are given. Statements by previous investigators concerning the morphology of the fungus are reviewed.

The work of previous investigators on the occurrence of strains or physiologic forms, homothallism, growth on artificial media, enzyme production, and the function of vitamins in the metabolism of the brown-rot fungus are reviewed, and results of experiments and studies made by the writers are reported.

The optimum temperature for the growth of the fungus lies between 75° and 80° F. Temperatures over 90° are distinctly unfavorable to its growth. Although the conidia will germinate at 32°, the fungus grows slowly at low temperatures.

The fungus grows best on an acid medium, but the point at which increased acidity stopped growth was found to depend not only on the hydrogen-ion concentration but also on the acid used. Thus,

one investigator found the limit for growth was pH 1.85 with sulphuric acid, pH 2.20 with phosphoric acid, pH 3.87 with formic acid, pH 4.45 with acetic acid, pH 4.5 with butyric acid, and slightly above pH 4.64 with salicylic acid. Apothecial production is also influenced by the hydrogen-ion concentration, with a maximum production of apothecia at pH 2.5.

A few ascospores were found to be viable five weeks after their discharge. The conidia produced naturally in the orchard are able to survive winter temperatures. Conidia produced during the summer are shorter lived than those produced in the late fall. High temperatures lessen the viability of conidia. No information is available concerning the longevity of the microconidia, since they have failed to germinate.

Rain, wind, birds, insects, and man are factors in the dissemination of the fungus, and of these the writers consider wind as the most important. Man can be an important agency in the spread of the disease on the harvested fruit through improper methods of picking and handling the fruit.

A list of host plants known to be susceptible is given in the text, but the list is not considered complete, since there has been no attempt to make a survey of these plants and because of the confusion that has existed regarding the classification of the fungus.

The fungus survives the winter in mummied fruits and in cankers. From these the fungus is propagated in early spring (1) through the production of conidia on mummies left on the trees, (2) through the production of apothecia and ascospores from those mummies that fall to the ground and become partly buried, and (3) in some sections through the production of conidia on twig cankers caused by the fungus. These three infection sources are discussed in detail. The overwintering on twig cankers is considered to be of less importance, except in certain limited sections, than the production of apothecia from partly buried mummies or the formation of conidia on mummies hanging on the trees.

The period of apothecial production from mummied fruits and the blossoming of peach trees have been found to coincide very closely over a period of years. Apothecia may be produced from mummies or fragments of mummies for many years, but the number of mummies that produce apothecia and the number of apothecia produced slowly diminish annually. Completely buried mummies tend to disintegrate more rapidly than those only partly buried.

Ascospores are discharged by pressure developed within the ascus and are shot for varying distances above the surface of the apothecium. Air currents undoubtedly play a large part in carrying away the discharged ascospores.

The blossom-blight, fruit-rot, mummy, canker, and twig-blight phases of the disease are considered in detail. Infection of the floral parts either by ascospores or by conidia may cause a reduction in the size of the crop, but the principal danger to the crop is that the infected blossoms may act as centers for the propagation of conidia which later infect the fruit as it matures.

Infection of the fruit may take place through the uninjured epidermis (i. e., by way of the stomata and hair sockets), but in the orchard the great majority of infections follow punctures of

the fruit made by the plum curculio, *Conotrachelus nenuphar* Hbst. Infection through wounds made by the oriental fruit moth, *Grapholitha molesta* Busck, is also quite common.

Twig canker formation may result from the infection of either the blossoms or the fruits. The fungus may remain alive over the winter in twig cankers, but in central Georgia and northern Virginia the writers have observed conidial production from cankers the following spring in only one instance. More profuse production of conidia on overwintered cankers has been observed by investigators in certain other sections.

Peach leaves, particularly those injured by the leaf-curl fungus, *Exoascus deformans* (Berk.) Fckl., occasionally may be infected by the brown-rot fungus and become infection sources.

Field experiments for the control of brown rot have demonstrated that the control of the plum curculio and the control of brown rot are closely correlated because control of the former prevents punctures of the epidermis through which brown-rot infections may take place. The curculio is well fitted to disseminate the brown-rot fungus, since its body is clothed with short bristles to which brown-rot spores readily adhere when the insect comes in contact with a rotted peach. Observations of entomologists indicate that the plum curculio feeds exclusively on sound fruit, so that direct dissemination of the fungus would largely be the result of accidental contact with a rotted peach. Therefore, in spite of the fact that the plum curculio is equipped by nature to disseminate brown-rot spores, its main importance in connection with brown rot is that it makes holes in the epidermis of the fruit through which the germ tubes of spores gain entrance to the inner tissues.

The fungus is intercellular in the tissues of the floral parts and of the fruit. The writers have been unable to demonstrate the mycelium of the fungus between the cells in the tissues of the twigs, but other investigators have observed mycelium in cavities caused by the destruction of the cells of the cortical parenchyma. The changes produced by the entrance of the fungus into the twig tissues are discussed in detail. The regeneration of tissues to cover the necrotic region presents no striking novelties and is illustrated by a series of photomicrographs.

The control of the brown-rot disease on the fruit depends largely upon an adequate and timely use of fungicides, coupled with proper measures for the control of the plum curculio. Spraying in central Georgia just as the blossoms were opening has checked blossom blight, but not enough to warrant recommendation for that section. Sanitary measures, such as the removal of diseased fruits, the plowing under of mummies, the pruning out of twig cankers, and the elimination of extra sources of infectious material, such as wild plum and seedling peach trees, which harbor the disease, are all of importance in a general control program. Because of the physical impossibility of completely eliminating all infectious material, these measures alone can not be relied upon to give adequate control of the disease. Sanitary measures when practiced as a community project and supplemented by a proper spray program are of assistance in controlling the disease, but the importance of a proper spray program can not be overemphasized.

Experiments with certain materials that give off vapors toxic to the brown-rot fungus are reported. Unfortunately, all the materials experimented with that were toxic to the fungus also imparted to the fruit a flavor or an odor that lessened or destroyed its market value. A successful fumigant must be toxic to the fungus, noninjurious to the fruit, odorless, tasteless, noninflammable, nontoxic to man, and of relatively low cost. A material embodying all these characteristics has not been found.

LITERATURE CITED

(1) ADERHOLD, R., and RUHLAND, W.
1905. ZUR KENNTNIS DER OBSTBAUM-SKLEROTINIEN. Arb. Biol. Reichsanst. Land u. Forstw. 4: [427]–442, illus.

(2) AMERICAN JOINT COMMITTEE ON HORTICULTURAL NOMENCLATURE.
1924. STANDARDIZED PLANT NAMES. Prepared by F. L. Olmsted, F. V. Coville, and H. P. Kelsey. 546 p. Salem, Mass.

(3) AMES, A.
1915. THE TEMPERATURE RELATIONS OF SOME FUNGI CAUSING STORAGE ROTS. Phytopathology 5: 11–19.

(4) ARCHIBALD, E. S.
1921. REPORT OF THE ACTING DOMINION BOTANIST. Canada Expt. Farms Rpt. 1920 (Sessional Paper 16): 58–63.

(5) ARTHUR, J. C.
1886. ROTTING OF CHERRIES AND PLUMS. OIDIUM FRUCTIGENUM S. & K. N. Y. Agr. Expt. Sta. Ann. Rpt. (1885) 4: 280–285, illus.

(6) ATKINS, W. R. G.
1916. SOME RECENT RESEARCHES IN PLANT PHYSIOLOGY. 328 p., illus. London and New York.

(7) BARRY, P.
1854. THE FRUIT GARDEN . . . 398 p., illus. Auburn, N. Y.

(8) BARSS, H. P.
1923. BROWN ROT AND RELATED DISEASES OF STONE FRUITS IN OREGON. Oreg. Agr. Expt. Sta. Circ. 53, 18 p., illus.

(9) BARTRAM, H. E.
1916. A STUDY OF THE BROWN ROT FUNGUS IN NORTHERN VERMONT. Phytopathology 6: 71–78.

(10) BERKELEY, G. H.
1926. BROWN ROT. Canada Dept. Agr., Div. Bot. Dominion Bot. Rpt. 1926: 64–65, illus.

(11) ———
1927. BLOSSOM BLIGHT ON PEACH. Canada Dept. Agr., Div. Bot. Dominion Bot. Rpt. 1927: 123.

(12) BLAKESLEE, E. B.
1919. USE OF TOXIC GASES AS A POSSIBLE MEANS OF CONTROL OF THE PEACH-TREE BORER. U. S. Dept. Agr. Bul. 796, 23 p., illus.

(13) BONORDEN, H. F.
1851. HANDBUCH DER ALLGEMEINEN MYKOLOGIE. 336 p., illus. Stuttgart.

(14) BROOKS, C., and COOLEY, J. S.
1917. TEMPERATURE RELATIONS OF APPLE-ROT FUNGI. Jour. Agr. Research 8: 139–164, illus.

(15) ——— and COOLEY, J. S.
1921. TEMPERATURE RELATIONS OF STONE FRUIT FUNGI. Jour. Agr. Research 22: 451–465, illus.

(16) ——— and FISHER, D. F.
1916. BROWN-ROT OF PRUNES AND CHERRIES IN THE PACIFIC NORTHWEST. U. S. Dept. Agr. Bul. 368, 10 p., illus.

(17) CHESTER, F. D.
1893. THE ROT OF THE PEACH AND OTHER STONE FRUITS. Peninsula Hort. Soc. [Del.] Trans. 6: 57–64.

(18) CONEL, J. L.
1914. A STUDY OF THE BROWN-ROT FUNGUS IN THE VICINITY OF CHAMPAIGN AND URBANA, ILLINOIS. Phytopathology 4: 93–101.

(19) COOK, M. T.
1921. THE BLOSSOM BLIGHT OF THE PEACH. Phytopathology 11: [290]–294, illus.
(20) COOLEY, J. S.
1914. A STUDY OF THE PHYSIOLOGICAL RELATIONS OF SCLEROTINIA CINEREA (BON.) SCHRÖTER. Ann. Missouri Bot. Gard. 1: 291–326.
(21) CORDLEY, A. B.
1899. BROWN ROT. (MONILIA FRUCTIGENA, PERS.) Oreg. Agr. Expt. Sta. Bul. 57, 15 p., illus.
(22) CORY, E. N.
1921. INSECTS OF THE YEAR. Peninsula Hort. Soc. [Del.] Trans. v. 10, no. 3, p. 61–64.
(23) COXE, W.
1817. A VIEW OF THE CULTIVATION OF FRUIT TREES, AND THE MANAGEMENT OF ORCHARDS AND CIDER; WITH ACCURATE DESCRIPTIONS OF THE MOST ESTIMABLE VARIETIES OF NATIVE AND FOREIGN APPLES, PEARS, PEACHES, PLUMS, AND CHERRIES, CULTIVATED IN THE MIDDLE STATES OF AMERICA . . . 253 p., illus. Philadelphia.
(24) CUNNINGHAM, G. H.
1922. BROWN-ROT, SCLEROTINIA CINEREA SCHROET. ITS APPEARANCE, CAUSE, AND CONTROL. New Zeal. Jour. Agr. 25: 83–93, illus.
(25) ———
1922. OCCURRENCE OF APOTHECIA OF BROWN-ROT IN NEW ZEALAND. New Zeal. Jour. Agr. 25: 177.
(26) ———
1922. THE SIGNIFICANCE OF APOTHECIA IN THE CONTROL OF BROWN-ROT OF STONE-FRUITS. New Zeal. Jour. Agr. 25: 225–230.
(27) CURTIS, K. M.
1928. THE MORPHOLOGICAL ASPECT OF RESISTANCE TO BROWN ROT IN STONE FRUIT. Ann. Bot. [London] 42: [39]–68, illus.
(28) DAVIDSON, F. R., and WILLAMAN, J. J.
1927. BIOCHEMISTRY OF PLANT DISEASES. IX. PECTIC ENZYMES Bot. Gaz. 83: 329–361, illus.
(29) DORAN, W. L.
1922. EFFECT OF EXTERNAL AND INTERNAL FACTORS ON THE GERMINATION OF FUNGUS SPORES. Bul. Torrey Bot. Club 49: 313–340, illus.
(30) DOWNING, A. J.
1876. THE FRUITS AND FRUIT TREES OF AMERICA; OR, THE CULTURE, PROPAGATION, AND MANAGEMENT, IN THE GARDEN AND ORCHARD, OF FRUIT TREES GENERALLY; WITH DESCRIPTIONS OF ALL THE FINEST VARIETIES OF FRUIT, NATIVE AND FOREIGN, CULTIVATED IN THIS COUNTRY. Rev. 2, 2 v., illus. New York.
(31) DUNN, M. S.
1926. EFFECTS OF CERTAIN ACIDS AND THEIR SODIUM SALTS UPON THE GROWTH OF SCLEROTINIA CINEREA. Amer. Jour. Bot. 13: 40–58, illus.
(32) EZEKIEL, W. N.
1921. SOME FACTORS AFFECTING THE PRODUCTION OF APOTHECIA OF SCLEROTINIA CINEREA. Phytopathology 11: 495–499.
(33) ———
1923. HYDROGEN-ION CONCENTRATION AND THE DEVELOPMENT OF SCLEROTINIA APOTHECIA. Science (n. s.) 58: 166.
(34) ———
1924. FRUIT-ROTTING SCLEROTINIAS. II. THE AMERICAN BROWN-ROT FUNGI. Md. Agr. Expt. Sta. Bul. 271: [87]–142, illus.
(35) ———
1925. PRESENCE OF THE EUROPEAN BROWN-ROT FUNGUS IN AMERICA. Phytopathology 15: 535–542, illus.
(36) ———
1926. FRUIT-ROTTING SCLEROTINIAS. III. LONGEVITY OF BURIED BROWN-ROT MUMMIES. Md. Agr. Expt. Sta. Bul. 284, p. [9]–22, illus.
(37) FANT, G. W.
1924. THE MANNER OF INFECTION OF PEACH TWIGS BY THE BROWN ROT FUNGUS. Phytopathology 14: 427–429.
(38) FREEMAN,
1868. [SPORES OF THE PEACH ROT.] Ill. Hort. Soc. Trans. (n. s.) 2: 48–49.

(39) GALLOWAY, B. T.
1889. BROWN ROT OF THE CHERRY. MONILIA FRUCTIGENA PERS. U. S. Dept. Agr. Rpt. 1888: 349–352.
(40) HARRISON, T. H.
1928. BROWN ROT OF FRUITS, AND ASSCCIATED DISEASES, IN AUSTRALIA. PART I. HISTORY OF THE DISEASE AND DETERMINATION OF THE CAUSAL ORGANISM. Jour. and Proc. Roy. Soc. N. S. Wales 62: 99–151, illus.
(41) HAWKINS, L. A.
1915. SOME EFFECTS OF THE BROWN-ROT FUNGUS UPON THE COMPOSITION OF THE PEACH. Amer. Jour. Bot. 2: 71–81.
(42) HILGARD, T. C.
1869. PEACH ROT AND ITS FORMS. Jour. Agr. [St. Louis] 5: 72.
(43) HINO, I.
1929. MICROCONIDIA IN GENUS SCLEROTINIA WITH SPECIAL REFERENCE TO THE CONIDIAL FORMS IN THE GENUS. Bul. Miyazaki Col. Agr. and Forestry 1: 67–90, illus. [In Japanese, with English résumé.]
(44) HONEY, E. E.
1928. THE MONILIOID SPECIES OF SCLEROTINIA. Mycologia 20: 127–157, illus.
(45) HULL, E. S.
1868. THE PLUM CURCULIO. Ill. Hort. Soc. Trans. (n. s.) 2: 264–269.
(46) HUMPHREY, J. E.
1893. ON MONILIA FRUCTIGENA. Bot. Gaz. 18: [85]–93, illus.
(47) JACKSON, H. S.
1915. PEAR CANKER, MONILIA SP. Oreg. Agr. Expt. Sta. Bien. Crop and Pest Rpt. 2: 271–272, illus.
(48) JEHLE, R. A.
1913. THE BROWN-ROT CANKER OF THE PEACH. Phytopathology 3: [105]–110, illus.
(49) KIRTLAND, J. R.
1855. PREMATURE DECAY OF THE PLUM. Florist and Hort. Jour. (Phila.) 4: 34–36. [Article dated 1855. No date given to volume.]
(50) KUNZE, G., and SCHMIDT, J. C.
1817. Mycologische Hefte 1, p. 80.
(51) LARSON, A. O.
1922. METALLIC MERCURY AS AN INSECTICIDE. Jour. Econ. Ent. 15: 391–395.
(52) MCCLINTOCK, J. A.
1921. PEACH DISEASE CONTROL. Ga. Agr. Expt. Sta. Bul. 139, 30 p., illus.
(53) ———
1930. THE BROWN ROT SITUATION IN 1929. Amer. Fruit Growers Mag. 50 (2): 11, 30, illus.
(54) MCCUBBIN, W. A.
1919. BROWN ROT OF STONE FRUITS. Agr. Gaz. Canada 6: 429–432.
(55) MANNS, T. F., and ADAMS, J. F.
1922. DISEASES OF PEACHES AND THEIR CONTROL. BROWN ROT. Del. Agr. Expt. Sta. Bul. 133: 27–28.
(56) MATHENY, W. A.
1913. A COMPARISON OF THE AMERICAN BROWN-ROT FUNGUS WITH SCLEROTINIA FRUCTIGENA AND S. CINEREA OF EUROPE. Bot. Gaz. 56: 418–432, illus.
(57) MIX, A. J.
1930. BROWN ROT, LEAF AND TWIG BLIGHT FOLLOWING PEACH LEAFCURL. Phytopathology 20: 265–266.
(58) MUHLEMAN, G. W.
1925. THE PECTINASE OF SCLEROTINIA CINEREA. Bot. Gaz. 80: 325–330.
(59) NORTON, J. B. S.
1902. SCLEROTINIA FRUCTIGENA. Acad. Sci. St. Louis, Trans. 12: 91–97, illus.
(60) ———, EZEKIEL, W. N., and JEHLE, R. A.
1923. FRUIT-ROTTING SCLEROTINIAS. I. APOTHECIA OF THE BROWN-ROT FUNGUS. Md. Agr. Expt. Sta. Bul. 256, p. 1–32; illus.
(61) ——— and EZEKIEL, W. N.
1924. THE NAME OF THE AMERICAN BROWN-ROT SCLEROTINIA. (Abstract) Phytopathology 14: 31–32.

(62) ORTON, W. A.
1905. PLANT DISEASES IN 1904. U. S. Dept. Agr. Yearbook 1904: 581–586.
(63) ———
1906. PLANT DISEASES IN 1905. U. S. Dept. Agr. Yearbook 1905: 602–611.
(64) PECK, C. H.
1881. REPORT OF THE BOTANIST. N. Y. State Mus. Nat. Hist. Ann. Rpt. 34: [24]–58.
(65) PERSOON, C. H.
1796–99. OBSERVATIONS MYCOLOGICÆ. SEU DESCRIPTIONES TAM NOVORUM, QUAM NOTABILIUM FUNGORUM. 2 v. in 1, illus. Lipsiae.
(66) ———
1801. SYNOPSIS METHODICA FUNGORUM . . . 2 v., illus. Gottingae.
(67) POLLOCK, J. B.
1909. NOTES ON PLANT PATHOLOGY. Mich. Acad. Sci. Rpt. 11: 48–54.
(68) ———
1918. THE LONGEVITY IN THE SOIL OF THE SCLEROTINIA CAUSING THE BROWN ROT OF STONE FRUITS. Mich. Acad. Sci. Rpt. 20: 279–280.
(69) POSEY, G. B.
1915. STUDIES ON MONILIA BLIGHT OF FRUIT TREES. Science (n. s.) 42: 583.
(70) QUAINTANCE, A. L.
1900. THE BROWN ROT OF PEACHES, PLUMS AND OTHER FRUITS. (MONILIA FRUCTIGENA, PERSOON). Ga. Agr. Expt. Sta. Bul. 50, p. [237]–269, illus.
(71) RAMSEY, G. B.
1925. SCLEROTINIA SPECIES CAUSING DECAY OF VEGETABLES UNDER TRANSIT AND MARKET CONDITIONS. Jour. Agr. Research 31: 597–632, illus.
(72) READE, J. M.
1908. PRELIMINARY NOTES ON SOME SPECIES OF SCLEROTINIA. Ann. Mycol. 6: [109]–115.
(73) REHDER, A.
1927. MANUAL OF CULTIVATED TREES AND SHRUBS HARDY IN NORTH AMERICA, EXCLUSIVE OF THE SUBTROPICAL AND WARMER TEMPERATE REGIONS. 930 p., illus. New York.
(74) RICE, W. H.
1929. CONTROL OF BROWN-ROT IN STONE-FRUITS. THE HENDERSON EXPERIMENTS WITH PEACH TREES, 1925–1929. New Zeal. Jour. Agr. 39: 97–100.
(75) RILEY, C. V.
1869. PLUM CURCULIO. *In* First Annual Report on the Noxious, Beneficial, and Other Insects of Missouri, p. 50–63. (Issued with 4th Ann. Rpt. Missouri State Bd. Agr.)
(76) ROBERTS, J. W.
1921. THE AGE OF BROWN-ROT MUMMIES AND THE PRODUCTION OF APOTHECIA. (Phytopath. Note) Phytopathology 11: 176–177.
(77) ——— and DUNEGAN, J. C.
1924. THE FUNGUS CAUSING THE COMMON BROWN ROT OF FRUITS IN AMERICA. Jour. Agr. Research 28: 955–960, illus.
(78) ——— and DUNEGAN, J. C.
1926. BLOSSOM BLIGHT OF THE PEACH. Phytopathology 16: 217–222.
(79) ——— and DUNEGAN, J. C.
1927. CRITICAL REMARKS ON CERTAIN SPECIES OF SCLEROTINIA AND MONILIA ASSOCIATED WITH DISEASES OF FRUITS. Mycologia 19: 195–205.
(80) ——— and DUNEGAN, J. C.
1927. PEACH BROWN ROT AND SCAB. U. S. Dept. Agr. Farmers' Bul. 1527, 14 p., illus.
(81) ROBERTSON, W. H.
1929. REPORT OF THE PROVINCIAL HORTICULTURIST AND INSPECTOR OF FRUIT PESTS. Brit. Columbia Dept. Agr. Ann. Rpt. (1928) 23: O 19–O 29, illus.
(82) RUDOLPH, B. A.
1925. MONILIA BLOSSOM BLIGHT (BROWN ROT) OF APRICOT. Calif. Agr. Expt. Sta. Bul. 383, 55 p., illus.
(83) SACCARDO, P. A.
1886–1906. SYLLOGE FUNGORUM . . . v. 4, 1886; v. 18, 1906. Patavii.

(84) SCHRÖTER, C. J.
1893. PILZE. *In* Cohn, F. Kryptogamen Flora Von Schlesien, Bd. 3, Halfte 2. Breslau.
(85) SCHWEINITZ, L. D. DE.
[1822]. SYNOPSIS FUNGORUM CAROLINAE SUPERIORIS SECUNDUM OBSERVATIONES. Soc. Nat. Cur. Lips. 1: 20–131, illus. [n. p]
(86) SCOTT, W. M.
1907. A PROMISING TREATMENT FOR BROWN ROT AND OTHER PEACH DISEASES. Amer. Pomol. Soc. Proc. 30: 39–48.
(87) ——— and AYRES, T. W.
1910. THE CONTROL OF PEACH BROWN ROT AND SCAB. U. S. Dept. Agr., Bur. Plant Indus. Bul. 174, 31 p., illus.
(88) SEAL, J. L.
1924. BIOLOGIC SPECIALIZATION IN SCLEROTINIA SP., THE ORGANISM CAUSING BROWN ROT OF FRUITS. Minn. Univ. Studies Biol. Sci. 5: [281]–286, illus.
(89) SELBY, A. D.
1898. PRELIMINARY REPORT UPON DISEASES OF PEACH. EXPERIMENTS IN SPRAYING PEACH TREES. Ohio Agr. Expt. Sta. Bul. 92, p. 179–268, illus.
(90) SMITH, E. F.
1889. SPOTTING OF PEACHES. Jour. Mycol. 5: 32–33.
(91) ———
1889. PEACH ROT AND PEACH BLIGHT. (MONILIA FRUCTIGENA, PERSOON.) Jour. Mycol, 5: 123–134.
(92) ———
1891. PEACH BLIGHT, MONILIA FRUCTIGENA, PERSOON. Jour. Mycol 7: 36–38.
(93) SNAPP, O. I.
1931. INSECTS ATTACKING THE PEACH IN THE SOUTH AND HOW TO CONTROL THEM. U. S. Dept. Agr. Farmers' Bul. 1557, 42 p., illus. (Revised.)
(94) STRASBURGER, E. A.
1921. TEXT-BOOK OF BOTANY. Eng. ed. 5 revised with German ed. 14, by W. H. Lang. 799 p., illus. London.
(95) TESCHE, W. C.
1927. BORDEAUX-OIL FOR BROWN ROT. Pacific Rural Press 114: 294.
(96) TILTON, J.
1807. LETTER TO RICHARD PETERS. Mem. Phila. Soc. Promoting Agr. 1: 192–197, 1815.
(97) VALLEAU, W. D.
1915. VARIETAL RESISTANCE OF PLUMS TO BROWN-ROT. Jour. Agr. Research 5: 365–396, illus.
(98) WARDER, J. A.
1867. AMERICAN POMOLOGY. APPLES. 744 p., illus. New York.
(99) WHITE, W. N.
1852. PLUMS AT THE SOUTH. Horticulturist 7: 401–405, illus.
(100) ———
1852. PEACHES AT THE SOUTH. Horticulturist 7: 555–558.
(101) WILLAMAN, J. J.
1920. PECTIN RELATIONS OF SCLEROTINIA CINEREA. Bot. Gaz. 70: 221–229.
(102) ———
1920. THE FUNCTION OF VITAMINES IN THE METABOLISM OF SCLEROTINIA CINEREA. Jour. Amer. Chem. Soc. 42: 549–585, illus.
(103) WILTSHIRE, S. P.
1919. THE PRODUCTION OF CONIDIA IN PURE CULTURES BY THE BROWN ROT FUNGUS OF THE APPLE. Univ. Bristol Agr. and Hort. Research Sta. Ann. Rpt. 1919: [34]–36.
(104) WINTER, G.
1883. UEBER EINIGE NORDAMERIKANISCHE PILZE. Hedwigia 22: 67–72, 129–131.
(105) WORMALD, H.
1919–20. THE 'BROWN ROT' DISEASES OF FRUIT TREES, WITH SPECIAL REFERENCE TO TWO BIOLOGIC FORMS OF MONILIA CINEREA BON. I–II. Ann. Bot. [London] 33: [361]–404, illus., 1919; 34: [143]–171, illus. 1920.

(106) ———
1921. ON THE OCCURRENCE IN BRITAIN OF THE ASCIGEROUS STAGE OF A 'BROWN ROT' FUNGUS. Ann. Bot. [London] 35: [125]–135, illus.
(107) ———
1927. FURTHER STUDIES OF THE BROWN-ROT FUNGI. II. A CONTRIBUTION TO OUR KNOWLEDGE OF THE DISTRIBUTION OF THE SPECIES OF SCLEROTINIA CAUSING BROWN ROT. Ann. Bot. [London] 41: [287]–299.
(108) ———
1928. THE PRESENT DISTRIBUTION OF THE BROWN-ROT FUNGI: ITS ECONOMIC SIGNIFICANCE. Jour. Min. Agr. [Gt. Brit.] 35: 741–750, illus.
(109) ———
1928. FURTHER STUDIES OF THE BROWN-ROT FUNGI. III. NOMENCLATURE OF THE AMERICAN BROWN-ROT FUNGI: A REVIEW OF LITERATURE AND CRITICAL REMARKS. Brit. Mycol. Soc. Trans. 13: 194–204.
(110) WORONIN, M.
1888. UEBER DIE SCLEROTIENKRANKHEIT DER VACCINIEN-BAEREN. ENTWICKELUNGSGESCHICHTE DER DIESE KRANKHEIT VERURSACHENDEN SCLEROTINIEN. 49 p., illus. (Mém. Acad. Imp. Sci. St. Pétersbourg, Ser. 7, t. 36, no. 6.)
(111) ———
1900. ÜBER SCLEROTINIA CINEREA UND SCLEROTINIA FRUCTIGENA. 38 p., illus. (Mém. Acad. Imp. Sci. St. Pétersbourg, Cl. Sci. Phys. Math. Ser. 8, v. 10, no. 5.)

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Division of Horticultural Crops and Diseases	E. C. AUCHTER, *Principal Horticulturist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

TECHNICAL BULLETIN No. 327 OCTOBER, 1932

COST OF PUMPING FOR DRAINAGE IN THE UPPER MISSISSIPPI VALLEY

BY

JOHN G. SUTTON
Assistant Drainage Engineer
Bureau of Agricultural Engineering
Division of Drainage and Soil Erosion Control

UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - Price 10 cents

TECHNICAL BULLETIN No. 327 OCTOBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

COST OF PUMPING FOR DRAINAGE IN THE UPPER MISSISSIPPI VALLEY[1]

By JOHN G. SUTTON

Assistant Drainage Engineer, Division of Drainage and Soil Erosion Control, Bureau of Agricultural Engineering

CONTENTS

	Page
Introduction	1
General description of plants studied	2
Collection and use of operation records	7
Pump ratings and tests	7
Original operation data	8
Explanation of tables	8
Determination of operating expenses	9
Fixed charges of interest and depreciation	9
Operating costs including fixed charges	14
Operation and cost records	15
Banner Special drainage and levee district	15
Coal Creek drainage and levee district	18
Green Bay levee and drainage district	23
Hartwell drainage and levee district	27
Hunt drainage and levee district	29
Indian Grave drainage and levee district	31
Lima Lake drainage and levee district	37
South Beardstown drainage and levee district	39
Bay Island drainage and levee district	44
Crane Creek drainage and levee district	49
Henderson County drainage and levee districts No. 1 and No. 2	51
Operation and cost records—Continued	
Scott County drainage and levee district	57
Eldred drainage and levee district	62
Fabius drainage and levee district	67
Mauvaisterre drainage and levee district	70
McGee Creek drainage and levee district	73
Valley City drainage and levee district	77
Summary of operation data	80
Average annual cost of pumping	83
Unit costs of pumping	86
Cost per brake horsepower-hour	87
Cost per acre-foot pumped	89
Cost per acre of watershed	90
Cost per acre assessed	91
Relation of cost of pumping to run-off depth	91
Backwater from dams	93
Application of data	94
Example 1	94
Example 2	96
Example 3	96
Factors affecting choice of power type	96
Summary and conclusions	98

INTRODUCTION

There are about 450,000 acres of river bottom land reclaimed by pumping in 63 organized drainage districts in the upper Mississippi Valley. Of this total, 170,000 acres lie along the Illinois River south of Hennepin, Ill., and about 280,000 acres along the Mississippi River between Savanna, Ill., and St. Louis, Mo.

During the last 30 years these lands have been organized into drainage districts, under State drainage laws, for the purpose of reclaiming swamp lands and improving the drainage of lands already in cultivation. Most districts are between 5 and 10 miles in length along the river and 2 to 4 miles in width, ordinarily extending from the bank of the river to the bluffs, which rise abruptly to a height of

[1] The studies reported herein could not have been carried out successfully without the hearty cooperation that was rendered by the commissioners, engineers, attorneys, and plant operators of the several drainage districts in obtaining the operation, cost, and test data. No less important have been the cost data supplied by the various electric, oil, coal, and machinery companies. Appreciation is due also to the firms which have cooperated in special tests of equipment, described more fully in progress reports for 1925 to 1929.

from 50 to 200 feet above the river. Levees have been built to protect these districts from overflow, and open ditches and tiles collect the interior drainage water and conduct it to the lower end of the district. Sluiceways through the levees have been provided by some districts, where the river stages are sufficiently low to permit gravity drainage, but most districts are so low that all the drainage water must be removed by pumping.

The earliest drainage pumping plants in this section were installed just prior to 1900. By 1930 there were 69 such plants (a few districts had more than one plant), which had a total rated capacity of about 26,400 horsepower and estimated pump capacity of about 4,100,000 gallons per minute. The total construction cost of these plants was approximately $3,700,000, and the total annual operating expenses have been estimated as $960,000.

Since about 1910, when the organization of considerable numbers of drainage pumping districts was begun, there has been much demand for information on the cost of pumping for drainage. Such information is needed by engineers in designing plants, by district officials in selecting equipment, and by companies supplying equipment or power for such plants. The Bureau of Agricultural Engineering [2] collected considerable information on the cost of pumping in 1916 and 1917, and again in 1923. However, few districts were keeping reliable records of operation of the plants, and data on expenditures are of little value unless related to the amounts of water pumped and power used. Apparently many of the plants were being operated inefficiently. A more comprehensive study of the cost of drainage pumping was commenced in 1925, particularly to consider the economy of different types of power and practical means for reducing costs. The results are given in the following pages.

This report presents the operation and cost data obtained from 17 typical drainage pumping plants in Illinois, Iowa, and Missouri. Although the data relate particularly to the upper Mississippi Valley, many of them are of general application. This is especially true of the unit costs based on quantity of water pumped and quantity of power used. Progress reports showing, for 1925 to 1929, the yearly operation and cost records and also the results of tests of the pumping equipment have been issued in mimeographed form.

GENERAL DESCRIPTION OF PLANTS STUDIED

The pumping plants studied are located along the Illinois River, and along the Mississippi River between Rock Island and the mouth of the Fabius River just south of Quincy, Ill. The location of each drainage district is shown in Figure 1. The principal features of the pumping equipment of each district are given in Table 1, including watershed area, date that the plant was first operated, and the design factors of the pumps.

[2] During the period of collecting the data presented herein, the agricultural-engineering investigations of the Department of Agriculture were administered by the Bureau of Public Roads.

FIGURE 1.—Location of drainage districts studied relative to cost of pumping

TABLE 1.—*Principal pumping plant equipment of certain drainage districts in the upper Mississippi Valley*

Drainage district	Watershed area	Pumping unit No.	Year first operated	Power type	Commercial rating of motor or engine	Transmission from motor or engine to pump	Design factors of pumps						
							Size	Total head	Speed per minute	Capacity per minute	Efficiency	Run-off depth per 24 hours	
												Unit	Plant
	Acres				*Horsepower*		*Inches*	*Feet*	*Revolutions*	*Gallons*	*Per cent*	*Inch*	*Inch*
Banner Special	6,760	1	1916	Electric	250	Chain belt	36	19.5	225	36,250	76	0.284	0.366
		2	1916	do	75	do	20	19.5	275	10,500	73	.082	
Coal Creek	7,525	1	1914	do	100	Leather belt	20	18.0	315	12,500	78	.088	.264
		2	1914	do	100	do	20	18.0	315	12,500	78	.088	
		3	1914	do	100	do	20	18.0	315	12,500	78	.088	
Green Bay	14,000	1	1918	do	300	Direct connection	42	26.0	187	47,500	80	.180	.360
		2	1918	do	300	do	42	26.0	187	47,500	80	.180	
Hartwell	12,900	1	1915	do	150	Chain belt	30	21.0	300	22,500	75	.093	.554
		2	1915	do	150	do	30	21.0	300	22,500	75	.093	
		3	1915	do	150	do	30	21.0	300	22,500	75	.093	
		4	1929	do	458	Direct connection	48	22.0	327	67,000	81	.275	
Hunt	15,840	1	1928	do	250	do	36	18.5	257	35,000	81	.117	.256
		2	1928	do	250	do	36	21.0	435	41,500	80	.139	
Indian Grave	21,000	1	1918	do	200	Chain belt	36	17.0	355	36,000	79	.091	.273
		2	1918	do	400		36	17.0	355	36,000	79	.091	
		3	1918	do			36	17.0	355	36,000	79	.091	
Lima Lake	16,640	1	1928	do	250	Direct connection	36	24.0	277	35,000	81	.112	.355
		2	1928	do	250	do	36	24.0	435	41,000	80	.131	
		3	1928	do	250	do	36	24.0	277	35,000	81	.112	
South Beardstown	8,350	1	1918	do	100	Leather belt	26	25.5	310	12,000	84	.076	.382
		2	1918	do	150	do	30	27.0	310	16,000	80	.102	
		3	1918	do	150	do	30	27.0	310	16,000	80	.102	
		4	1918	do	150	do	30	27.0	310	16,000	80	.102	
Bay Island	52,000	1	1909	Steam	500	Direct connection	60	14.5	125	115,000	78	.117	.234
		2	1909	do	500	do	60	14.5	125	115,000	78	.117	
Crane Creek	6,230	1	1913	do	250	do	36	24.0	187	30,000	73	.255	.255
Henderson County	22,400	1	1913	do	300	do	48	15.0	150	55,000	76	.130	.260
		2	1913	do	300	do	48	15.0	150	55,000	76	.130	
		1	1928	Electric	350		48	20.0	250	55,000	80	.130	.260
		2	1928	do	350		48	20.0	250	55,000	80	.130	
Scott County	12,500	1	1913	Steam	420	Direct connection	45	24.0	200	45,000	75	.191	.352
		2	1913	do	155	do	24	24.0	275	16,000	72	.068	
		3	1928	Semi-Diesel	150	Leather belt	30	18.0	350	22,000	80	.093	
Eldred	9,300	1	1921	Diesel	250	Direct connection	36	19.0	240	37,500	77	.214	.522
		2	1911	Steam	190	do	36	10.0	133	37,500	75	.211	
		3	1911	do	150	do	24	10.0	170	17,000	75	.097	
		3	1929	Diesel	120	Leather belt	24	10.0	170	17,000	75	.097	

Fabius	14,900	1	1917	do	250	Direct connection	42	16.5	200	47,500	80	.169	.338
		2	1917	do	250	do	42	16.5	200	47,500	80	.169	
Mauvaisterre	7,180	1	1926	do	120	do	30	17.0	257	20,600	81	.152	.152
McGee Creek	15,700	1	1926	Semi-Diesel	150	Leather belt	30	18.0	350	22,000	80	.074	.401
		2	1926	do	150	do	30	18.0	350	22,000	80	.074	
		3	1926	do	150	do	30	18.0	350	22,000	80	.074	
		4	1926	do	150	do	30	18.0	350	22,000	80	.074	
		5	1915	Steam	225	Direct connection	36	10.0	180	31,000	73	.105	
Valley City	7,160	1	1922	Semi-Diesel	150	do	36	21.0	257	25,000	85	.185	.265
		2	1922	do	100	do	24	20.0	257	10,750	85	.080	

As one of the primary objects of the investigation was to obtain the cost of pumping with the different types of power, careful consideration was given to selecting representative plants using electric, oil-engine, and steam power. Electric power was used by the Banner Special, Coal Creek, Green Bay, Hartwell, Hunt, Indian Grave, Lima Lake, and South Beardstown plants during all the time that records were being obtained from them. Steam power was used by Bay Island, Crane Creek, Henderson County, and Scott County plants when record taking began. The first two of these used steam power as long as the records were continued. The Henderson County plant substituted electric for all steam equipment in 1928. The Scott County plant in the same year installed a semi-Diesel unit to do the ordinary pumping, and thereafter used the steam equipment for stand-by service.

All ordinary pumping was done with oil-engine equipment by the Eldred, Fabius, Mauvaisterre, McGee Creek, and Valley City plants, as long as records were continued on them. The Eldred and McGee Creek plants had also stand-by steam equipment, which was used occasionally during flood conditions or while the oil-engine equipment was being repaired.

The suction bays are generally of concrete. Less expensive construction was used at the Henderson County and the Eldred plants, where the earth excavation was merely covered with riprap and sheet piling was used to inclose the building foundations.

All the engines, motors, and pumps were set on concrete foundations resting on piling, except that no piling was used at the McGee Creek plant.

The pumps were all of the divided or double-suction centrifugal type with closed-vane impellers, except two single-suction pumps at the Eldred plant and one at the Scott County plant and the three pumps with screw-type impellers at the Hunt, Lima Lake, and Hartwell plants, which also were single suction.

The suction pipes were constructed of riveted or welded steel, except those at the Banner Special, Green Bay, and Fabius plants, where concrete was used. All of the suction pipes have been expanded or belled, at least to some extent, in order to reduce entrance losses and to permit the pump to lower the water in the suction bay without taking air and losing its priming.

All the discharge pipes were built of riveted or welded steel and run over the levees, except at the Green Bay and Valley City plants, where concrete sluiceways run through the levees. Most of the steel discharge pipes were expanded near the pumps to a diameter 2, 4, or 6 inches greater than the pump-flange connection to decrease friction losses and improve the plant efficiency. However, but few of the pipes were expanded at the outer end to reduce exit losses.

A large amount of accessory equipment is necessary in each type of plant. Each electric plant is equipped with switchboard, starting and stopping equipment, priming pump driven by a small motor, and the necessary switches and wiring. The transformer equipment is usually owned by the company supplying current. Each steam plant contains boilers, feed-water pumps, necessary piping, lighting equipment, steam ejector for priming, and usually condensers and mechanical stokers. Most of the steam equipment is old and much less efficient than modern installations, and the coal consumption is usually quite high. Each oil-engine plant has a priming pump driven by a small

gasoline engine, except the Fabius plant, where priming is done with a steam ejector. Cooling water is drawn from driven wells, except at the Fabius plant, where water is obtained from the suction bay. In each plant there is a small reciprocating pump to pump the cooling water, supplemented, except in the Scott County and McGee Creek plants, by a storage tank to supply cooling water in case the pump stops temporarily. Each plant has an electric generator to supply light and a steel tank for the storage of fuel oil.

COLLECTION AND USE OF OPERATION RECORDS

PUMP RATINGS AND TESTS

Numerous ratings were made of each pump to determine the quantity of water pumped at each speed against the different lifts. More comprehensive tests were made frequently to determine the efficiencies of the pumps and the over-all efficiencies of the pumping unit. During such tests measurements were made of the static lift, the total head on the pump, the speed of the pump, the quantity of water discharged, and the power used by the motor or engine. The pump and over-all efficiencies were computed from an average of usually four such tests.

The static lift was determined before and after the discharge of a pump had been measured, by reading the suction and discharge bay gauges and applying elevation corrections if necessary.

The total head on the pump was determined by measuring the suction and discharge pressure heads with columns of water or mercury and applying the proper elevation and velocity head corrections.

The discharge of the pumps was determined by measuring the velocity of the water in the suction or discharge pipe with a pitot tube, at 10 points located on the circumferences of rings of equal area. On a very few occasions the discharge was measured by means of a current meter, which is considered less accurate.

During the tests of the electric plants, the current used by the motors was measured by timing a certain number of revolutions of the disk wheel in the watt-hour meter with a stop watch, and then multiplying the speed of the wheel by the proper constant to obtain the horsepower input. Electric meters are legally required to record within 2 per cent of the correct amount of current.

The indicated horsepower of the steam engines was measured with a Crosby steam indicator, the springs of which were calibrated by the Bureau of Standards, Department of Commerce. The mean of several indicator cards was taken to determine the power used at each speed.

The brake horsepower developed by each oil engine was estimated from the measured oil consumption of the engine, which was multiplied by a constant factor assumed by the engineer in charge of the tests after considering the manufacturer's guarantees for new equipment, the condition of the engine, and the probable power required by the pump. Brake tests were made on the McGee Creek and Scott County semi-Diesel units during 1928; therefore the records of power used at those plants are probably more accurate than those of the other oil-engine plants.

ORIGINAL OPERATION DATA

Daily records kept by the operator of each plant included the amount of rainfall, the elevations of water in the suction and discharge bays, the time of starting and of stopping each pump, and the speeds of the pumps. At the plants using electric power, daily readings of the watt-hour meter were recorded. At the steam plants, which used coal for fuel, the coal on hand usually was recorded monthly, but the plant operator had no means of measuring the amount accurately. The author measured the coal pile occasionally to obtain more accurate figures. At the oil-engine plants, computations of fuel oil on hand usually were made from semimonthly measurements of the depth of oil in the tanks, which apparently were recorded quite accurately.

The rainfall records kept at the plant were compared with the official Weather Bureau records from near-by stations, and the latter were used at a few plants when the operator failed to record a general rain or where his records were obviously in error.

Every attempt was made to determine the amount of water pumped as accurately as possible, and the amounts shown probably do not vary over 5 per cent on an average from the actual amounts. Errors might be due to a number of causes, including variations in the conditions of operation from those that obtained during tests. For example, weeds or débris in a pump would decrease its discharge without giving visible evidence of the obstruction. The records of the plant operators were checked by computing the amount of water pumped each month both from the operators' records and from the fuel or electric power consumed according to the rates of consumption determined during tests.

EXPLANATION OF TABLES

For each plant studied, a table is given showing the operation data for each month and year of the period during which records were kept on that plant. These data comprise the amounts of rainfall, of water pumped, and of power used, besides the average over-all efficiencies and loads on motor or engine.

After several tests of a plant had been made, rating curves were plotted which showed for each unit the discharge of the pump for the different lifts and speeds. The rate of pumping by each unit was determined for each day from these curves, using the average speed and average lift for that day. The quantity pumped was determined from this rate and the time the unit was operated during the day. The work done by each unit in acre-feet-feet was computed for each day by multiplying the quantity pumped, expressed in acre-feet, by the average static lift. The daily run-off expressed in inches depth over the entire watershed area, was computed from the quantity pumped by all the units of the plant.

The average lift for the month was computed by dividing the number of acre-feet-feet pumped during the month by the number of acre-feet, thus obtaining a weighted average and not the average difference in the elevations of the suction and discharge bays.

For the electric and steam plants, the amount of operation by each, expressed in rated horsepower-hours, was obtained by multiplying the commercial horsepower rating of each unit by the hours it operated. The amounts of power used per acre-foot, without respect to

lift, are based upon determinations of total indicated and brake horsepower-hours developed each month. The indicated horsepower-hours were determined for the electric plants by multiplying kilowatt-hours by 1.341. For the steam-operated plants, indicated horsepower-hours were computed from the average speed and hours operated each day, according to the rate of power used as shown by the indicator cards taken during tests. Brake horsepower-hours for electric and for steam plants were computed from the indicated horsepower-hours, by using estimated mechanical efficiencies of the motors or engines based in part upon figures given by the manufacturers. They have averaged about 90 per cent, and are believed to be not more than 2 to 4 per cent in error in any case.

For the oil-engine plants, brake horsepower-hours were estimated after 1927 from a consideration of the amount of fuel oil consumed, the known brake horsepower required to drive similar pumps at other plants, and the pump manufacturer's curves of estimated brake horsepower required. The average estimated load on the engine was multiplied by the hours of operation to determine the rated horsepower hours. Indicated horsepower-hours were computed for each unit by dividing the brake horsepower-hours by the engine efficiency as estimated after considering figures given by the manufacturer. This procedure is believed to be better than estimating the indicated horsepower-hours from fuel consumption, as was done for the 1925 and 1926 records. It is believed that all results are within 5 to 10 per cent correct. The mechanical efficiencies used have averaged between 70 and 80 per cent for the different plants.

In computing the efficiencies of the pumps, the mechanical efficiencies of belt, chain, and gear drives have been assumed as about 95 per cent in each instance and the efficiency of direct connection as 100 per cent.

The pump efficiency depends on the head operated against and on the design of the pump. The maximum efficiency usually ranged from 70 to 80 per cent at or near the maximum designed head, but unless the speed was greatly reduced the efficiency was much lower at the low and medium heads.

The over-all efficiency in each case represents the combined efficiency of the engine or motor, the transmission, the pump, and the suction and discharge piping.

The load on engine or motor is the ratio of the brake horsepower-hours developed to the rated horsepower-hours for the same period.

DETERMINATION OF OPERATING EXPENSES

The total cost of pumping includes not only the yearly operating expenses of the plant, but also interest on the money invested and depreciation to return the cost of the plant when it is worn out. These last two items, known as fixed charges, often receive little consideration although they frequently amount to nearly half the total cost of pumping.

FIXED CHARGES OF INTEREST AND DEPRECIATION

Interest on the original cost has been computed for all plants at 6 per cent, because it is the legal rate. In some instances bonds have been sold by drainage districts which carry less than 6 per cent interest. In the majority of cases, however, discounts and other

expenses incidental to selling the bonds have made the interest rate on the net money received considerably greater than 6 per cent, and in some instances it was almost 8 per cent.

To compute depreciation accurately, three factors must be known: The first cost of the plant, its life, and its salvage value. For a plant that is still operating, the first cost is the only one of these factors which can be determined with accuracy. The life of equipment can only be estimated. The computations herein neglect the salvage value, as it will be very small. The sinking-fund method of computing depreciation is used as most suitable for a drainage district. The annual depreciation charge is taken as an amount which, collected every year and invested at 4 per cent interest compounded annually, would equal the cost of the equipment at the end of its estimated life.

The estimated fixed charges with related data are shown in Table 2. For the electric plants they have amounted to approximately 8 per cent of the installation or first cost, for steam plants to about 9 per cent, and for oil-engine plants to 8.5 to 9.5 per cent.

TABLE 2.—*Computation of fixed charges on drainage pumping plants in the upper Mississippi Valley*

Plant	Power type	Year constructed	Commercial rating of motors or engines	Area assessed for cost of plant	Cost of plant		Buildings, foundations, suction bay, discharge bay			Motors or engines		
					Total	Per horsepower	Cost	Estimated life	Annual depreciation	Cost	Estimated life	Annual depreciation
			Horsepower	*Acres*	*Dollars*	*Dollars*	*Dollars*	*Years*	*Dollars*	*Dollars*	*Years*	*Dollars*
Banner Special	Electric	1915–16	325	3,585	34,360	105.72	23,970	33	362	3,000	22	88
Coal Creek	do	1913–14	300	6,396	19,964	66.55	10,464	30	187	3,000	20	101
Green Bay	do	1917–18	600	8,816	142,500	237.50	86,500	33	1,306	16,000	25	384
Hartwell	do	1914–15 and 1928	908	8,900	82,083	90.40	34,795	33	526	14,188	25	341
Hunt	do	1927–28	500	15,137	85,694	171.39	43,694	33	660	12,000	25	288
Indian Grave	do	1917–18	600	18,296	89,000	148.33	53,400	33	807	9,500	25	228
Lima Lake	do	1927–28	750	12,227	103,200	137.60	43,200	33	652	17,000	25	408
South Beardstown	do	1917–18	550	7,352	74,700	135.82	43,950	30	784	8,250	20	277
Bay Island	Steam	1908–09	1,000	23,591	96,800	96.80	49,800	33	752	15,000	25	360
Crane Creek	do	1912–13	250	5,021	21,480	85.92	10,480	20	352	3,000	20	101
Henderson County	do	1912–13	600	15,005	77,640	129.40	35,140	35	477	12,500	15	624
	Electric	1928 [1]	700	15,005	[2] 71,917	102.74	32,917	20	1,105	15,000	20	504
Scott County	Steam	1912–13	575	9,514	49,370	85.86	17,000	33	257	10,000	20	336
	do	1928 [3]	575	9,514	[4] 20,000			[5] 20			[5] 20	
	Semi-Diesel	1927–28	150	9,514	33,820	225.47	16,320	33	246	9,000	15	449
Eldred (unit No. 1)	Diesel	1920–21	250	8,438	42,300	169.20	7,700	30	137	23,350	16	1,070
Eldred (units Nos. 2 and 3)	Steam	1921 [3]	340	8,438	[4] 26,000			[5] 25			[5] 25	
Eldred (unit No. 3)	Diesel	1928 [6]	120	8,438	[7] 17,065			17			17	
Eldred (unit No. 2)	Steam	1928 [6]	190	8,438	[7] 14,250			17			17	
Fabius	Diesel	1916–17	500	14,700	63,150	126.30	27,400	33	414	16,250	14	888
Mauvaisterre	do	1925–26	120	4,009	27,312	227.60	9,612	30	171	8,000	16	367
McGee Creek	Semi-Diesel	1925–26	600	10,800	66,150	110.25	12,150	30	217	31,000	15	1,548
	Steam	1927 [3]	225	10,800	[4] 3,000			[5] 10			[5] 10	
Valley City	Semi-Diesel	1921–22	250	4,800	57,740	230.96	27,640	33	417	13,000	16	596

[1] Year in which rebuilt.
[2] Estimated value after being rebuilt.
[3] Year in which it began to be operated as stand-by equipment.
[4] Estimated value in year commenced operating as stand-by equipment.
[5] Estimated life from date it began to be operated as stand-by equipment.
[6] In 1928, Diesel engine of 120 horsepower replaced 150 horsepower steam engine to operate unit No. 3.
[7] Valuation in 1929 (p. 67).

TABLE 2.—*Computation of fixed charges on drainage pumping plants in the upper Mississippi Valley*—Continued

Plant	Power type	Year constructed	Transformers, boilers, oil tanks, starting equipment, etc.			Pumps, suction pipes, discharge pipes			Total depreciation per year	Interest on cost of plant	Total annual fixed charges			
			Cost	Estimated life	Annual depreciation	Cost	Estimated life	Annual depreciation			Amount	Ratio to cost of plant	Per horsepower installed	Per acre assessed
			Dollars	*Years*	*Dollars*	*Dollars*	*Years*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Per cent*	*Dollars*	*Dollars*
Banner Special	Electric	1915–16	3,100	18	121	4,290	33	65	636	2,062	2,698	7.85	8.30	0.75
Coal Creek	do	1913–14	2,500	18	97	4,000	30	71	456	1,198	1,654	8.28	5.51	.26
Green Bay	do	1917–18	15,000	18	585	25,000	33	378	2,653	8,550	11,203	7.86	18.67	1.27
Hartwell	do	1914–15 and 1928	7,430	18	290	25,670	33	388	1,545	4,925	6,470	7.88	7.13	.73
Hunt	do	1927–28	12,000	18	468	18,000	33	272	1,688	5,142	6,830	7.97	13.66	.45
Indian Grave	do	1917–18	16,100	18	628	10,000	33	151	1,814	5,340	7,154	8.04	11.92	.39
Lima Lake	do	1927–28	17,000	18	663	26,000	33	393	2,116	6,192	8,308	8.05	11.08	.68
South Beardstown	do	1917–18	7,500	18	292	15,000	30	267	1,620	4,482	6,102	8.17	11.09	.83
Bay Island	Steam	1908–09	20,000	18	780	12,000	33	181	2,073	5,808	7,881	8.14	7.88	.33
Crane Creek	do	1912–13	5,000	15	250	3,000	33	45	748	1,289	2,037	9.48	8.15	.41
Henderson County	do	1912–13	20,000	15	939	10,000	35	136	2,236	4,658	6,894	8.88	11.49	.46
	Electric	1928 [1]	12,000	18	468	12,000	20	403	2,480	4,315	6,795	9.45	9.71	.45
Scott County	Steam	1912–13	16,370	16	750	6,000	33	91	1,434	2,962	4,396	8.90	7.65	.46
	do	1928 [3]		[5] 20			[5] 20		672	1,200	1,872		3.26	.20
	Semi-Diesel	1927–28	3,500	15	175	5,000	33	76	946	2,029	2,975	8.80	19.83	.31
Eldred (unit No. 1)	Diesel	1920–21	5,500	16	252	5,750	30	103	1,562	2,538	4,100	9.69	16.40	.49
Eldred (units Nos. 2 and 3)	Steam	1921 [3]		[5] 25			[5] 25		624	1,560	2,184		6.42	.26
Eldred (unit No. 3)	Diesel	1928 [6]		17			17		720	1,024	1,744	10.22	14.53	.21
Eldred (unit No. 2)	Steam	1928 [6]		17			17		601	855	1,456	10.22	7.66	.17
Fabius	Diesel	1916–17	6,000	14	328	13,500	33	204	1,834	3,789	5,623	8.90	11.25	.38
Mauvaisterre	do	1925–26	2,200	16	101	7,500	30	134	773	1,639	2,412	8.83	20.10	.60
McGee Creek	Semi-Diesel	1925–26	6,000	15	300	17,000	30	303	2,368	3,969	6,337	9.58	10.56	.59
	Steam	1927 [3]		[5] 10			[5] 10		250	180	430		1.91	.04
Valley City	Semi-Diesel	1921–22	7,400	16	339	9,700	33	147	1,499	3,464	4,963	8.60	19.85	1.03

[1] Year in which rebuilt.
[3] Year in which it began to be operated as stand-by equipment.
[5] Estimated life from date it began to be operated as stand-by equipment.
[6] In 1928, Diesel engine of 120 horsepower replaced 150 horsepower steam engine to operate unit No. 3.

CONSTRUCTION COST

The construction cost of the plant (column 6, Table 2) could not be determined precisely in every case, because of incomplete records. The costs shown include an allowance, usually 5 per cent of the contract price, to cover overhead expenses such as legal, engineering, and commissioners' fees. The figures for the older plants and for those built by day labor may be in error as much as 2 to 5 per cent. The first cost for each plant except the Mauvaisterre and the McGee Creek includes the cost of a residence for the plant operator.

The costs are shown to have ranged from $66.55 to $237.50 per horsepower installed, the averages for different types of power being $106 per horsepower for 3 steam plants, $139 per horsepower for 8 electric plants, and $155 per horsepower for 6 oil-engine plants. The steam plants cost less because they were built in a period of lower prices.

The construction costs and consequently the fixed charges of plants have been greatly affected by the price basis at the time of construction. This must be considered in comparing the total costs of pumping by plants built at widely different times. Construction-cost index numbers have ranged, during 1909 to 1929, from 91 to 251 per cent of 1913 costs, as shown in Table 3.

TABLE 3.—*Engineering News-Record construction-cost index numbers, 1909 to 1931*

Cost index		Cost index		Cost index		Cost index	
Year	Number	Year	Number	Year	Number	Year	Number
1909	90. 92	1915	92. 58	1921	201. 81	1927	206. 24
1910	96. 33	1916	129. 58	1922	174. 45	1928	206. 78
1911	93. 43	1917	181. 24	1923	214. 07	1929	207. 02
1912	90. 70	1918	189. 20	1924	215. 36	1930	202. 85
1913	100. 00	1919	198. 42	1925	206. 68	1931	181. 35
1914	88. 56	1920	251. 28	1926	208. 03		

The construction costs and fixed charges have been affected also by such conditions as quicksand encountered in foundation work and floods occurring during construction. In some instances, the plants have been built by day labor or by contracting the work in small units, thus eliminating the profit and cost of a general contractor. It is questionable whether this procedure is to be generally recommended; yet the unusually low cost of the McGee Creek plant was due to this method of construction.

In comparing costs and charges it is necessary to consider also the quality of buildings and equipment. Aesthetic qualities are not so important in a drainage plant as in many projects of a public nature; yet an appearance of permanence and dependability is no doubt of value, especially in those districts that must sell their bonds to outsiders. Also a well-constructed plant probably aids landowners to secure private loans more readily. For these reasons it seems desirable to build a better building than one barely adequate to house the equipment. Poor quality usually results in a shorter life, and increased maintenance costs especially in the later years of the life of the plant.

LIFE OF EQUIPMENT

The pumping-plant equipment was divided into four classes for the purpose of estimating depreciation. The life of buildings, foundations, and suction and discharge bays was estimated from 20 to 35 years.

The engines or motors were estimated to last from 14 to 25 years. In general, a somewhat longer life was allowed for electric motors than for the steam or oil engines. Little reliable information is available regarding the life of oil engines in drainage work, as few have been operating long enough to have worn out. A life of 14 to 18 years was estimated for the transformers and wiring, boilers and piping, fuel-oil tanks, priming outfits, and other accessory equipment. The pumps and piping were assumed to have a life of 20 to 35 years. However, it is possible that the development of more efficient types of pumps may cause present equipment to become obsolete and to be replaced before it is actually worn out.

The life of structures and equipment depends considerably upon the care given them. A pumping plant operated by a man who thoroughly understands the machinery and who is industrious enough to take care of it will operate economically much longer than a similar plant in the hands of an unskilled or careless person. The rapid depreciation of many drainage pumping plants has resulted from the employment of unskilled operators because they could be obtained at low salaries.

FIXED CHARGES ON EQUIPMENT USED FOR STAND-BY SERVICE

Three districts had old steam equipment which was nearly worn out but which was operated during periods of heavy run-off. It was necessary to determine a fair cost of operating such stand-by equipment in order to compute the total cost of pumping for each district. When equipment is thus abandoned for regular service, its life is increased and its fixed charges reduced. A depreciated value at the time it was abandoned for regular pumping was estimated after considering its first cost, past length of service, condition, cost of replacement, and utility. On each of the stand-by units, annual fixed charges were computed as a whole, rather than in four parts as for the equipment for regular service.

The value of the Eldred steam unit of 1921, after having operated since 1911, was estimated as $26,000, and the life as stand-by equipment was estimated as 25 years. Units No. 2 and No. 3 were revalued at the end of 1928 because the small steam engine was abandoned and a Diesel engine was substituted (p. 62). The value of the McGee Creek steam unit in 1927 was estimated as only $3,000, due to its very poor condition. This unit ordinarily will be used very little as the semi-Diesel units have a combined run-off capacity of 0.3 inch per 24 hours. The value of the Scott County steam units in 1928 was estimated as $20,000 after having operated since 1913. The values of both the Eldred and the Scott County steam plants were taken as being approximately equal to their first costs minus their estimated accumulated depreciation funds.

OPERATING COSTS INCLUDING FIXED CHARGES

The annual costs of pumping, comprising both operating and fixed charges, are shown for each plant hereinafter with the operation records for that plant. The annual totals are shown also in Table 47 with the unit costs. The operating expenses as obtained from the district's, court's, or electric company's records are classified as power or fuel, labor, repairs and supplies, lubricating oils and gasoline, miscellaneous, and overhead expenses.

The cost of the power used by all electric plants except the Henderson County was taken as that actually billed by the power companies, although the amount billed may differ slightly from that actually used because the power companies' readings were not always taken just at the end of the month. The cost of coal and fuel oil is the cost of the fuel actually used. The labor cost includes all labor of operating the plant. In addition to the wages paid in cash, each district except the McGee Creek and the Mauvaisterre furnished the operator a house to live in free of rent. Miscellaneous costs include insurance, telephone, repairs to operator's house, and other smaller items.

Part of the annual overhead expenses of the drainage district has been charged to the pumping plant. This part was computed by multiplying the total overhead expenses for the district by the ratio of the other operating expenses for the pumping plant, including fixed charges, to the other operating expenses for all the district, including fixed charges. Fixed charges on the levee and other works of the district except the pumping plant were estimated as 9 per cent of their first cost. The total overhead expenses of the district include commissioners' treasurer's, attorney's, court, printing, and miscellaneous costs, and such general engineering costs as were not chargeable to construction, operation, or maintenance of specific works. Some districts incurred heavy interest charges for money borrowed to meet current expenses. Such interest was not included in the overhead costs, as it would have greatly affected the comparison of operating expenses of the pumping plants. Such expenses were the result of a poor financial condition, rather than of inefficient plant operation.

OPERATION AND COST RECORDS

The pumping operations and cost of each district investigated are given in considerable detail in the following pages, so that the requirements of similar districts may be approximated and the factors affecting the unit costs may be studied. Nearly all the data relate to the 6-year period 1925 to 1930, inclusive, which included 3 wet years, 1926, 1927, and 1929; 2 dry years 1925 and 1930, and 1 average year 1928. The average amount of pumping for the 6 years was slightly above the average for the previous 10 years. Extreme floods occurred along the Illinois River during 1926 and 1927 and along the Mississippi in 1929. The pumping conditions during 1928 were about average. These drought and flood periods gave opportunity to study plant operation under extreme conditions, and the records were carried on for a long enough period so that the averages represent typical conditions.

BANNER SPECIAL DRAINAGE AND LEVEE DISTRICT

The Banner Special drainage and levee district, on the west side of Illinois River, is approximately 6½ miles long and three-fourths of a mile wide. The watershed area now comprises 6,760 acres; the run-off from 1,540 acres previously drained by the plant was diverted in 1921.

The pump house, a substantial brick structure on a concrete foundation, contains the two pumping units described in Table 1. The 36-inch pump can be operated at four speeds, from 160 to 230 revolutions per minute, by changing the pulleys, and the 20-inch pump at three speeds, from 190 to 271 revolutions per minute. The pulleys are difficult to change, however, as short sections of the shafts must be

removed; consequently the speed has not been changed as frequently as desirable. The suction pipes are built of concrete and are expanded to an area approximately five times that at the pump flange.

OPERATION OF PLANT

Operation records were kept at this plant from 1925 to 1927, inclusive, and are given in Table 4. During 1925, the rainfall was small and evenly distributed; consequently the river stages were low and only a small amount of pumping was done. The records for 1926 and 1927 were greatly affected by flood conditions. The Copperas Creek diversion levee broke as a result of excessive rains on September 1 and 3, 1926, and flooded approximately 2,700 acres in the district. The plant operated almost continuously during September and water was pumped down to a normal stage. The river levee broke near the upper end of the district on October 7, 1926, and flooded the plant. Pumping was not resumed until September 1927. Continuous pumping was then necessary for about three weeks to get the water down to a normal level in the suction bay. The river levee again broke and flooded the plant in December, 1927. Records of operation were discontinued after 1927.

TABLE 4.—*Monthly operations of Banner Special drainage pumping plant, 1925 to 1927*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity							
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*	*Indicated horsepower-hours*	*Brake horsepower-hours* [1]	*Per cent*	*Per cent*
January	0.48	0			0					
February	1.99	2.25	1,265	10.02	40,250	23,940	25.4	22.9	54	72
March	1.89	2.05	1,156	13.48	42,450	25,910	30.1	27.1	62	74
April	1.20	.49	277	12.85	10,280	7,350	35.6	32.0	50	86
May	1.27	.33	188	10.22	5,990	4,340	31.0	27.9	45	88
June	3.75	1.05	589	8.29	17,630	11,500	26.2	23.6	44	79
July	2.99	.40	227	8.02	6,740	3,710	21.9	20.2	50	68
August	3.48	.18	101	8.18	4,280	1,950	25.8	23.3	43	55
September	4.11	.06	36	7.14	1,460	700	26.1	23.3	38	58
October	3.13	.38	213	8.37	8,940	4,630	29.2	25.6	39	61
November	2.81	1.15	649	8.94	26,750	14,700	30.4	27.1	40	66
December	.51	.64	360	9.52	15,330	8,170	30.4	27.3	43	64
Total or average	27.61	8.98	5,061	10.38	180,100	106,900	28.3	25.4	50	72
1926										
January	1.23	.31	176	7.53	7,120	3,780	28.8	25.9	36	64
February	1.84	1.18	665	8.88	29,550	14,950	30.2	27.0	40	61
March	2.20	1.59	896	12.63	30,180	18,030	27.0	24.6	64	73
April	2.23	3.00	1,689	15.80	62,150	40,500	32.2	29.2	67	79
May	1.16	.85	479	14.06	17,190	11,500	32.2	28.9	60	80
June	4.46	1.11	628	12.90	23,220	14,260	30.4	27.5	58	74
July	6.61	.66	369	10.41	14,080	8,460	30.7	27.6	46	72
August	3.21	1.73	975	11.51	36,860	20,700	28.5	25.7	56	68
September	11.55	13.06	7,360	10.15	227,730	173,280	31.6	28.8	44	93
October [2]	2.31	1.90	1,072	20.64	41,760	32,310	40.4	36.8	70	94
Total or average	36.80	25.39	14,309	12.02	489,840	337,770	31.7	28.7	52	84
1927										
September	6.80	10.66	6,003	2.40	168,110	125,730	28.1	25.6	12	91
October	3.18	2.93	1,651	9.77	51,050	39,830	32.4	29.2	42	95
November	2.61	1.35	762	12.82	25,490	17,700	31.2	28.0	56	84
December [3]	1.49	1.06	600	15.02	20,390	15,730	35.2	31.9	59	94
Total or average	14.08	16.00	9,016	5.47	265,040	198,990	29.6	26.9	25	91

[1] Motor efficiencies assumed as 88 to 91.9 per cent.
[2] Plant flooded and pumping stopped Oct. 7, 1923; pumping resumed Sept. 5.
[3] Plant flooded Dec. 21, 1927.

During the growing season water in the suction bay was held below 34 feet on the gage to prevent damage to crops, while during the dry season and winter it was allowed to reach a stage of 35 to 37 feet. The capacity of the plant was sufficient to hold the water to these normal stages in the suction bay except for one day, August 1, 1926, and after the levees broke. The maximum 24-hour run-off was 0.499 inch per 24 hours.

The efficiency of the pumps could have been improved by reducing the speeds at the low lifts, but the lowest speed never was used except during tests. The over-all efficiency could have been improved also by keeping the pipes and pumps free from trash. Much clogging of the suction bay occurred before the trash screen was put in place in March, 1925. Sometimes the discharge pipes did not run full. When a stick was removed from the left suction of the larger pump on one occasion, the discharge increased from 38,390 to 45,330 gallons per minute, while the power consumption decreased from 33.7 to 32.1 indicated horsepower-hours per acre-foot. Repairs were needed on the priming equipment, the water-seal glands, and the suction and discharge pipes to stop air leaks.

COST OF PUMPING

The monthly rates at which the district was billed for power during 1925 were as follows: First 7,600 kilowatt-hours at 3.5 cents, next 7,600 kilowatt-hours at 2.75 cents, and additional kilowatt-hours at 2 cents. Discounts of 5 per cent for off-peak pumping and 5 per cent for payment of the bill within 10 days were allowed. The minimum charge was $12 per horsepower per year on the normal rating of the motors driving the pumps.

The monthly rates in effect during 1926 and 1927, which resulted in a lower net cost to the district when the consumption was more than approximately 13,000 kilowatt-hours per month were: First 3,500 kilowatt-hours at 5 cents, next 7,000 kilowatt-hours at 3.5 cents, and additional kilowatt-hours at 2.3 cents. A discount of 10 per cent was allowed for payment within 10 days, and a quantity discount was allowed after all other discounts were deducted, as follows: On first $100, none; on next $100, 10 per cent; on next $300, 20 per cent; on next $500, 30 per cent; on all over $1,000, 40 per cent. The minimum bill was $10 per horsepower per year on the normal rating of the motors driving the pumps. The company reserved the right to discontinue service for any three consecutive hours of any 24-hour period.

An 11-year record of the power consumed and its cost is given in Table 5. The power consumption during 1925 was only 53 per cent of the 11-year average, and the unit cost of current was higher than in 1926 or 1927 because of the smaller consumption. The lower rates during 1926 and 1927 were due to the large quantities of power consumed during the floods and to the fact that there were several months when the plant was not operating, and hence was not billed for the minimum charge. The cost per acre varied somewhat less than the cost per kilowatt-hour.

TABLE 5.—*Power used by Banner Special drainage pumping plant, 1917 to 1927*

Year	Amount of power		Cost of power		
	Kilowatt-hours	Per cent of average	Total	Per kilowatt-hour	Per acre assessed
			Dollars	*Cents*	*Dollars*
1917	158,400	78	3,310.14	2.09	0.92
1918	104,322	51	2,703.71	2.59	.75
1919	215,980	106	5,318.74	2.46	1.48
1920	205,890	101	4,620.88	2.24	1.29
1921	180,730	89	4,412.53	2.44	1.23
1922	294,210	144	6,378.12	2.17	1.78
1923	151,030	74	3,871.69	2.56	1.08
1924	284,870	140	6,729.19	2.36	1.88
1925	107,440	53	2,935.11	2.73	.82
1926	339,300	166	6,182.78	1.82	1.72
1927	200,980	99	3,448.13	1.72	.96
Average	203,923	100	4,537.37	2.23	1.27

TABLE 6.—*Operating costs, including fixed charges, for Banner Special drainage pumping plant, 1925–1927*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 dollars	2,698	2,935	780	322	20	41	186	6,982
1926 do	2,698	6,183	821	220	80	125	459	[1] 10,586
1927 do	2,698	3,448	1,279	1,936	39	136	268	[2] 9,804
Per cent of 1925 total	38.6	42.0	11.2	4.6	0.3	0.6	2.7	100

[1] Plant flooded Oct. 7, 1926; pumping resumed Sept 5, 1927.
[2] Plant flooded again Dec. 21, 1927.

The total operating costs are shown in Table 6. The repairs and supplies for 1927 include an unusual item of about $1,600 for the repair of motors damaged during the floods. Minor repairs to the plant were frequent, as it had been operating since 1916, with apparently little maintenance work being done prior to 1925. In comparing the total operating expenses with those of other plants, it should be remembered that the plant was built in a period of lower prices, which resulted in lower fixed charges.

COAL CREEK DRAINAGE AND LEVEE DISTRICT

The Coal Creek drainage and levee district, on the west side of the Illinois River, began pumping in 1898 with a steam plant, which was replaced in 1914 with the present electric plant. There is a ditch extending along the bluff, which diverts nearly all the hill water from the district. The minimum stage of the river is affected by backwater from a dam below the plant.

The pump house is a large stucco building with concrete foundation walls, and contains the three pumping units described in Table 1. Three sets of pulleys for each motor are proportioned so as to give pump speeds of 306, 335, and 367 revolutions per minute. The dry vacuum pump, size 12 by 12 inches, is driven by a 10-horsepower motor.

OPERATION OF PLANT

Daily operation records were kept on this plant from 1927 to 1930, inclusive, and the monthly summary figures are given in Table 7. Fairly reliable records have been kept on this plant since it began operating in 1914, and the yearly totals for these 17 years are shown in Table 8.

TABLE 7.—*Monthly operations of Coal Creek drainage pumping plant, 1927 to 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity				Indicated horsepower-hours	Brake horsepower-hours [1]		
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
January	1.08	1.66	1,039	10.35	41,280	36,900	47.6	43.0	30	108
February	1.46	3.84	2,406	15.84	107,250	96,575	53.8	48.6	40	109
March	5.92	6.57	4,120	14.31	158,420	152,160	49.5	44.7	40	116
April	7.42	8.36	5,244	16.99	215,130	202,160	51.7	46.6	45	114
May	7.68	7.21	4,522	17.94	193,850	178,655	53.0	47.8	46	112
June	3.76	6.12	3,840	18.81	185,650	161,750	56.5	51.0	46	106
July	2.34	2.08	1,306	11.57	47,430	44,150	45.3	40.9	35	113
August	2.75	.99	622	8.64	21,210	19,250	41.5	37.5	29	110
September	3.60	.77	483	7.66	15,970	14,800	41.1	37.1	26	112
October	4.12	3.41	2,140	13.27	80,850	75,200	47.1	42.5	39	112
November	3.37	1.97	1,238	10.06	43,930	38,800	42.0	37.9	33	107
December	2.58	2.89	1,811	15.20	78,610	65,400	48.4	43.7	43	101
Total or average	46.08	45.87	28,771	15.39	1,189,580	1,085,800	50.6	45.7	42	110
1928										
January	.42	2.87	1,800	13.69	72,990	63,300	47.2	42.6	40	105
February	1.41	2.88	1,807	13.87	73,700	62,200	46.2	41.7	41	102
March	1.05	1.73	1,082	11.68	40,270	35,600	44.1	39.8	36	107
April	3.29	2.74	1,716	12.49	65,870	58,700	45.9	41.4	37	108
May	2.47	1.63	1,025	10.94	37,110	31,700	41.5	37.5	36	103
June	6.15	2,62	1,640	9.37	56,850	52,200	42.7	38.5	30	111
July	5.63	2.02	1,269	11.87	47,740	42,500	44.9	40.6	36	108
August	4.81	1.38	865	9.82	30,490	26,200	40.6	36.7	33	104
September	4.35	.83	522	8.24	17,520	15,600	40.1	36.2	28	108
October	3.46	1.29	808	8.22	27,160	24,600	40.8	36.9	28	110
November	3.42	2.39	1,497	9.92	52,790	47,100	42.2	38.1	32	108
December	1.90	2.36	1,479	11.70	55,260	50,400	45.7	41.3	35	110
Total or average	38.36	24.74	15,510	11.41	577,750	510,100	44.1	39.8	36	107
1929										
January	3.94	2.80	1.758	12.25	66,910	60,200	45.9	41.5	37	109
February	.61	2.09	1,308	11.99	48,880	43,500	44.6	40.3	37	108
March	3.31	5.26	3,300	16.63	153,610	125,000	50.8	45.9	45	98
April	5.31	4.78	2,995	19.26	160,990	123,300	55.2	49.9	48	93
May	4.78	4.39	2,752	17.82	133,400	107,400	52.3	47.3	47	98
June	4.14	2.67	1,671	14.47	67,720	56,600	45.4	41.0	44	101
July	6.52	5.34	3,348	13.77	118,400	121,800	48.8	44.1	39	125
August	1.02	1.15	721	10.05	25,120	22,400	41.7	37.6	33	108
September	2.41	.45	285	7.83	9,750	8,400	39.5	35.7	27	104
October	3.69	1.11	696	8.48	27,080	[2] 13,600	26.2	23.7	44	61
November	1.88	1.94	1,214	8.77	48,050	29,300	32.4	29.2	37	74
December	.89	1.25	782	8.24	30,400	18,400	31.5	28.5	36	73
Total or average	38.50	33.23	20,830	14.48	890,310	729,900	47.0	42.4	42	99
1930										
January	3.63	1.95	1.225	10.82	52,980	32,000	35.0	31.6	42	73
February	2.17	4.00	2,507	13.84	105,860	77,000	41.2	37.2	46	88
March	1.75	3.14	1,972	14.34	80,320	59,700	40.6	36.7	48	90
April	1.98	1.80	1,132	12.85	52,310	32,200	38.1	34.4	46	74
May	1.87	1.57	986	12.95	48,170	26,600	36.2	32.7	49	67
June	2.28	.61	386	8.35	15,020	8,600	29.9	27.0	38	69
July	.64	.30	186	7.78	7,130	4,400	31.7	28.7	34	75
August	2.28	.12	73	6.68	2,730	1,600	29.5	26.6	31	71
September	2.60	.21	131	7.98	5,050	1,600	16.4	14.8	67	38
October	1.66	.37	234	7.48	8,910	4,900	28.1	25.3	37	67
November	2.11	.39	242	6.40	8,930	5,200	28.8	26.0	30	70
December	.34	.52	328	6.54	12,120	7,200	29.5	26.6	30	72
Total or average	23.31	14.98	9,402	12.25	399,530	261,000	37.2	33.6	45	79

[1] Motor efficiencies assumed as 90.2 to 90.3 per cent.
[2] Meter out of order during October, 1929.

The earlier records kept by the district are probably not quite as accurate as those obtained after 1927, but the hours of operation agree quite closely with determinations from the meter readings of the power company. Nearly all of the rainfall data were taken from the Weather Bureau records at Beardstown. The plant was flooded April 15, 1922, and pumping was resumed August 14. As some pumping done after the flood was not properly recorded, the records for 1922 are omitted from the averages and are not considered in the following discussion. The electric meter was out of order during 1924 and 1925, and probably recorded less current than was actually used. For this reason the plant efficiencies for these two years (Table 8) are of doubtful accuracy.

TABLE 8.—*Yearly operations of Coal Creek drainage pumping plant, 1914 to 1930*

Year	Rainfall	Water pumped		Average static lift	Rated horsepower hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity				*Indicated horsepower hours*	*Brake horsepower hours* [1]		
	Inches	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
1914	25.50	11.05	6,923	9.73	274,570	199,875	38.7	34.8	34	88
1915	42.36	29.72	18,634	11.32	778,630	527,950	38.0	34.2	41	82
1916	32.00	25.73	16,130	12.24	725,350	528,300	43.9	39.5	38	88
1917	29.88	18.10	11,353	11.53	489,290	360,925	42.6	38.4	37	89
1918	37.28	17.23	10,791	10.56	466,310	325,875	40.5	36.4	36	84
1919	30.97	19.69	12,347	12.15	566,250	382,050	41.5	37.3	40	81
1920	32.04	22.68	14,213	13.75	615,320	487,990	46.0	41.4	41	96
1921	37.01	18.25	11,450	9.66	469,760	333,710	39.1	35.2	34	86
1922 [2]	21.37	27.33	17,142	8.37	599,860	551,175	43.1	38.8	27	111
1923	32.20	18.51	11,604	9.10	435,850	332,775	38.5	34.6	32	92
1924	32.75	20.30	12,738	10.63	558,550	[3] 224,800	[3] 23.7	[3] 21.3	62	49
1925	34.09	17.74	11,125	8.26	434,240	[3] 167,975	[3] 20.2	[3] 18.2	[3] 56	[3] 47
1926	49.49	45.19	28,332	13.04	1,116,330	953,600	45.1	40.6	40	103
1927	46.08	45.87	28,771	15.39	1,189,580	1,085,800	50.6	45.7	42	110
1928	38.36	24.74	15,510	11.41	577,750	510,100	44.1	39.8	36	107
1929	38.50	33.23	20,830	14.48	890,310	729,900	47.0	42.4	42	99
1930	23.31	14.98	9,402	12.25	399,530	261,000	37.2	33.6	45	79
Average	[4] 35.11	23.94	15,010	12.14	624,226	463,289	41.4	37.3	40	90

[1] Motor efficiencies assumed as 90.0 to 90.3 per cent.
[2] Plant flooded Apr. 15, 1922; pumping resumed Aug. 14, 1922; records incomplete.
[3] Meter out of order; current consumption recorded probably low.
[4] Records for 1922 omitted from averages.

The annual rainfall ranged from 23.31 inches in 1930 to 49.49 inches in 1926. The rainfall for the 6-year period from 1925 through 1930 averaged 38.30 inches, while the 16-year average was 35.11 inches, a difference of 3.19 inches. Evidently the years 1925 to 1930 were moderately wet years. The average run-off for the 6 years was 30.29 inches, and that for the 16 years was 23.94 inches, a difference of 6.35 inches. The run-off was increased not only by the greater rainfall, but also by the greater seepage resulting from the higher average river stages. Seepage was very heavy during the 1926 and 1927 floods.

The monthly lift varied between 6.20 feet in September, 1925, and 19.26 feet in April, 1929. However, this latter figure would have been considerably higher had the plant been able to hold the water in the suction bay at the optimum stage, but the water level was from 2 to 4 feet above normal during the worst flood conditions. The discharge bay reached a stage of 102 feet twice during 1927, and in order to hold the water in the suction bay to a stage of 80 feet the plant

would have had to operate against a maximum lift of 22 feet. The minimum lift is ordinarily about 8 feet.

The capacity of the plant was not sufficient to drain the district properly, especially during 1927 and 1929. The water level in the suction bay is ordinarily held between 78 and 80 feet on the gage, but for nearly two months in the spring of 1927 it ranged between 82 and 84 feet, even though all units were operated continuously. As a result of the poor drainage obtained, very little corn could be grown in this district that year. In 1929 there were several occasions when the stage of the suction bay reached 82 feet. Because of the overload on the motors, the pumps could not be operated safely at high speed, except at very high lifts when the load was somewhat reduced. The efficiency of operation could have been increased by operating the pumps at low speed during low-water periods. This was not done until October, 1929, when complete rating curves plainly showed the economy of such adjustment.

COST OF PUMPING

The rate paid for electric current during 1927 was as follows: First 6,400 kilowatt-hours at 5 cents, next 12,800 kilowatt-hours at 3.5 cents, and additional kilowatt-hours at 2.3 cents. Discounts and other contract conditions were the same as for the Banner Special district for 1927. (P. 17.)

On May 1, 1928, the district began operating under the optional off-peak rate, and continued pumping on this rate through 1930. The cost of power under this rate comprised:

(1) A primary charge of $9 per horsepower per year, chargeable at 75 cents per horsepower per month on the total rated horsepower of all motors connected excepting motors used to drive the auxiliary equipment. The district had 300 horsepower connected, and the primary charge was $225 monthly, except during May, 1928, when only 200 horsepower was connected.

(2) A charge for current used. For day service, 7 a. m. to 9 p. m., the charge was 3.2 cents per kilowatt-hour up to the equivalent of 60 hours' use of the maximum demand and 1.2 cents per kilowatt-hour for all additional current, during each month. For night service, 9 p. m. to 7 a. m., the charge was 1.2 cents per kilowatt-hour for all current used. For payment within 10 days after the date of the bill, a discount of 0.2 cent per kilowatt-hour was allowed. The above rates were based upon delivery and metering of service at 2,300 volts; the customer owned and maintained all the equipment beyond the point of delivery.

The district had the option of operating either on the off-peak rate or on the standard day rate in effect prior to May 1, 1928. It was estimated that by operating off-peak instead of on the day rate, the district saved $1,018 or 16 per cent during the period May 1 to December 31, 1928, $1,034 or 8 per cent in 1929, but only $85 or 1 per cent in 1930. Even though the district increased the operator's monthly salary by $25 for pumping at night, the off-peak rate was considerably cheaper for the district during the first three years it was used. The saving in 1930 was small because the amount of pumping necessary was small.

The cost of power used from 1914 to 1930, is shown in Table 9. A reduction in the rate was made in 1916. The cost per kilowatt-hour was greatest in 1921, and per acre assessed in 1927. The off-peak rate used during 1928, 1929, and 1930 was cheaper than any previous rate.

TABLE 9.—*Power used by Coal Creek drainage pumping plant, 1914 to 1930*

Year	Amount of power		Cost of power		
	Kilowatt-hours	Per cent of average	Total	Per kilowatt-hour	Per acre assessed
			Dollars	*Cents*	*Dollars*
1914	199,650	43	5,790.31	2.90	0.91
1915	527,550	112	11,353.72	2.15	1.78
1916	528,300	113	9,834.11	1.86	1.54
1917	362,300	77	7,464.47	2.06	1.17
1918	324,700	69	7,607.80	2.34	1.19
1919	382,600	81	8,483.09	2.22	1.33
1920	488,000	104	11,336.51	2.32	1.77
1921	329,500	70	11,171.40	3.39	1.75
1922	569,700	121	11,721.09	2.06	1.83
1923	330,900	70	8,049.13	2.43	1.26
1924	229,200	49	6,804.13	2.97	1.06
1925	167,700	36	5,309.68	3.17	.83
1926	953,500	203	16,032.23	1.68	2.51
1927	1,085,500	231	17,658.68	1.63	2.76
1928	510,200	109	9,500.84	1.86	1.49
1929	728,900	155	11,955.00	1.64	1.87
1930	263,200	56	5,904.00	2.24	.92
Average	469,494	100	9,763.31	2.08	1.53

The earlier tests showed that the efficiencies of all three pumps were very low, and practically the same. After a new impeller was installed in pump No. 2 in September, 1929, tests at selected heads and all speeds showed an average saving of 19 per cent in the power required by this unit.

The operating costs including fixed charges are shown in Table 10. The fixed charges are very small because the first cost of the plant was low. The annual costs of repairs and supplies including gasoline for the four years ended in 1930, were $1,100, $944, $1,584, and $452, respectively, and of lubricating oils $26, $19, $18, and $30. The repairs and supplies for 1927 include $472 for two new belts and $280 for the repair of the roof. In 1928 the repair of a motor that was burned out cost $635. In 1929, the building of new concrete supports for the discharge pipes cost $259 and the installation of a new impeller cost $948. The overhead expenses were large for 1926 due to a court suit for damages, and for 1928 due to the payment of accumulated legal expenses.

TABLE 10.—*Operating costs including fixed charges for Coal Creek drainage pumping plant, 1914–1930*

Year	Fixed charges	Electric power	Labor	Repairs and supplies and miscellaneous items	Overhead charged to pumping plant	Total
1914 dollars	1,654	5,790	750	68	82	8,344
1915 do	1,654	11,354	1,353	201	141	14,703
1916 do	1,654	9,834	1,243	582	174	13,487
1917 do	1,654	7,464	1,160	376	206	10,860
1918 do	1,654	7,608	1,311	182	142	10,897
1919 do	1,654	8,483	1,386	97	58	11,678
1920 do	1,654	11,337	1,473	368	446	15,278
1921 do	1,654	11,171	1,450	325	237	14,837
1922 do	1,654	11,721	678	188	187	14,428
1923 do	1,654	8,049	1,046	171	253	11,173
1924 do	1,654	6,804	1,156	524	208	10,346
1925 do	1,654	5,310	996	636	431	9,027
1926 do	1,654	16,032	1,646	582	2,382	22,296
1927 do	1,654	17,659	1,381	1,147	416	22,257
1928 do	1,654	9,501	1,244	984	1,149	14,532
1929 do	1,654	11,955	1,738	1,662	226	17,235
1930 do	1,654	5,904	1,371	632	255	9,816
Average [1] do	1,654	9,641	1,294	534	425	13,548
Per cent of total	12.2	71.2	9.6	3.9	3.1	100.0

[1] Plant flooded Apr. 15, 1922; pumping resumed Aug. 14. Costs for 1922 omitted from averages.

GREEN BAY LEVEE AND DRAINAGE DISTRICT

The Green Bay levee and drainage district, in Lee County, Iowa, is divided about equally between lower bottom lands which were flooded when the power dam was built across the Mississippi at Keokuk and second bottom lands the drainage of which was affected more or less by construction of the dam. The water backed up by the dam surrounds the district all the year, and a large amount of seepage into the district has resulted.

The pump house is a substantial reinforced concrete structure and contains two pumping units described in Table 1. The speed of the pumps can not be changed, but as the lift is almost constant, it is not as important to vary the speed as for the other plants studied.

Each pump discharges into a rectangular sluiceway 4½ by 5½ feet in section, which connects with a larger reinforced concrete sluiceway 6½ feet square running under the levee. About midway in the main sluiceway there is an opening in the top, approximately 12 inches in diameter, to release any air that may accumulate. The suction pipes also are made of reinforced concrete.

OPERATION OF PLANT

Operation records were kept on this plant during 1925 and 1926. The monthly summaries are given in Table 11. The run-off during 1925 of 21.65 inches is much below the average for this plant. Figure 2 shows the daily operation records for 1925. These operating conditions are typical of a plant that operates against a high constant lift such as is produced by the dam at Keokuk, Iowa. The fluctuations in the river stages usually are not great, and a large and fairly constant quantity of seepage results. In 1926, the amount of pumping was very large because of the break in the Skunk River diversion levee in September, which flooded the district. At one time the water rose about 7 feet higher than the pump-house floor but, as the

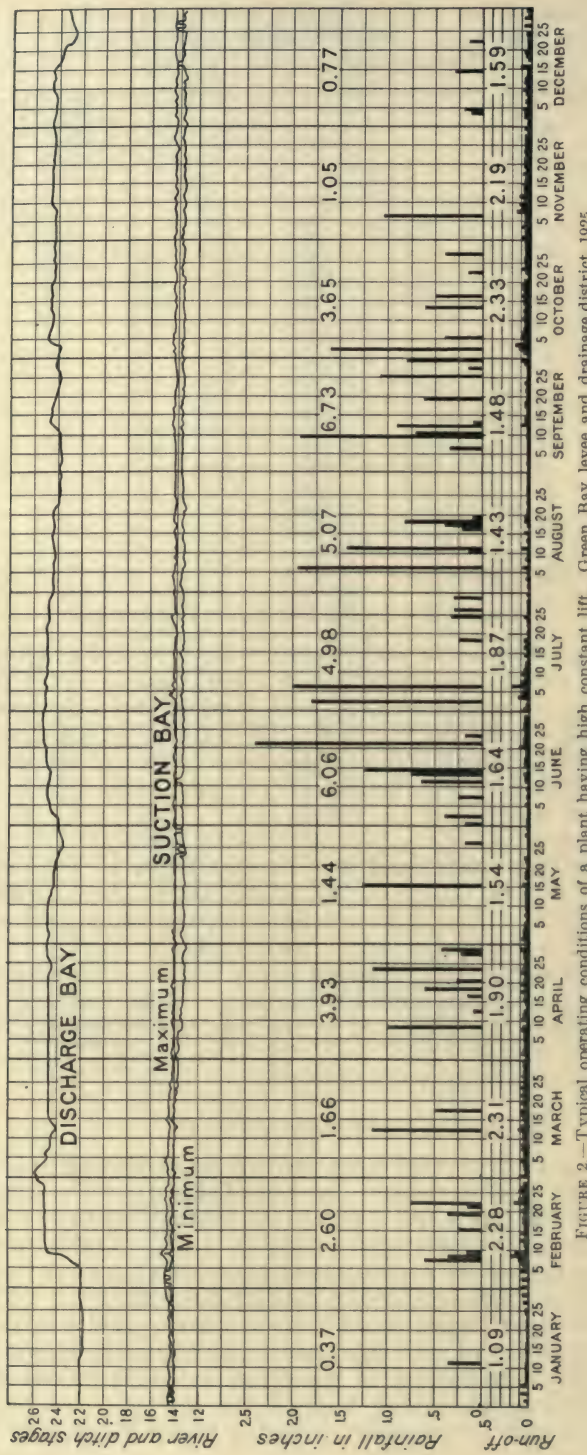


FIGURE 2.—Typical operating conditions of a plant having high constant lift. Green Bay levee and drainage district, 1925

construction of the building was water-tight, the pumping plant was able to continue operating until the diversion levee was repaired and the water pumped down to a normal stage. Both pumps operated continuously from September 17 to November 18, 1926. In that year the plant pumped 56.69 inches of run-off, which was the second greatest yearly run-off pumped by any of the plants during the 5-year period.

TABLE 11.—*Monthly operations of Green Bay drainage pumping plant, 1925 and 1926*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity							
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*	*Indicated horsepower-hours*	*Brake horsepower-hours* [1]	*Per cent*	*Per cent*
January	0.37	1.09	1,270	7.70	24,470	22,970	24.3	22.3	44	116
February	2.60	2.28	2,656	9.99	61,190	57,740	29.2	26.8	47	116
March	1.66	2.31	2,699	10.63	65,000	61,930	30.8	28.3	47	118
April	3.93	1.90	2,214	10.98	55,330	51,910	31.4	28.9	48	116
May	1.44	1.54	1,800	10.97	45,000	42,330	31.5	29.0	48	116
June	6.06	1.64	1,913	11.39	50,090	46,640	32.7	30.1	48	115
July	4.98	1.87	2,187	11.30	56,390	51,380	31.5	29.0	49	112
August	5.07	1.43	1,672	10.73	40,970	38,210	30.6	28.2	48	115
September	6.73	1.48	1,729	10.59	41,650	38,850	30.1	27.7	48	115
October	3.65	2.33	2,723	11.12	68,510	64,090	31.6	29.0	48	115
November	1.05	2.19	2,550	10.99	64,330	59,510	31.3	28.8	48	114
December	.77	1.59	1,859	10.57	46,480	43,340	31.3	28.8	46	115
Total or average	38.31	21.65	25,272	10.67	619,410	578,900	30.7	28.3	48	115
1926										
January	.73	1.67	1,948	10.80	48,650	44,800	30.8	28.3	48	114
February	1.80	1.59	1,851	10.50	45,740	42,460	30.8	28.3	47	114
March	2.62	1.64	1,911	9.93	47,280	44,560	31.3	28.7	44	116
April	1.80	2.36	2,756	11.52	70,640	65,650	31.9	29.4	50	114
May	1.75	1.60	1,861	11.40	47,580	44,770	32.3	29.7	48	116
June	9.55	2.99	3,490	11.23	88,840	82,730	31.8	29.2	48	115
July	2.45	1.43	1,673	10.76	41,400	38,140	30.6	28.1	48	114
August	3.75	1.39	1,627	10.88	40,230	36,920	30.4	28.0	49	113
September	13.37	11.08	12,927	4.47	297,990	242,790	25.2	23.3	24	101
October	2.99	17.34	20,230	.59	446,400	373,150	24.7	22.9	3	104
November	2.98	11.12	12,969	5.45	301,400	262,810	27.2	25.1	28	108
December	1.30	2.48	2,896	10.88	71,940	67,190	31.1	28.6	48	115
Total or average	45.09	56.69	66,139	5.43	1,548,090	1,345,970	27.3	25.2	27	108

[1] Motor efficiencies assumed as 91.9 to 92.5 per cent.

Unusual precipitation in 1926 made it necessary to operate both pumps on June 14, on September 8 and 9, and again on September 14, prior to the break in the levee; it had been necessary to operate the units simultaneously only once during the preceding seven years. Both pumps are operated together only when necessary, as the maximum power demand charge is thus approximately doubled. The capacity of the pumping plant is considered adequate, although after the heavy rainfall that occurred during 1926, the suction bay rose rapidly. The maximum 24-hour run-off pumped was 0.564 inch, in 1926.

The static lift was more nearly constant at this plant than at any other investigated, because the water in the discharge bay was held at a nearly constant elevation by the dam at Keokuk and because fluctuation of the water in the suction bay was reduced by a large

lake in the district. The static lift ranged from 7.70 feet to 11.52 feet, omitting the months when the district was flooded. The average static lift has probably been very close to 10½ feet.

COST OF PUMPING

The contract for power provided for a maintenance and investment charge of $1 per month per kilowatt of the maximum demand registered by the demand meter, in addition to service charges for power used each month as follows: First 8,000 kilowatt-hours at 1.5 cents and additional kilowatt-hours at 0.6 cent. A discount of 10 per cent of the service charge was allowed when the bill was paid within 10 days. The demand charge has been based on 305 kilowatt-hours practically all the time the plant has been in operation, except when two pumps were operated simultaneously. The time of operating the pumps was controlled by the load dispatcher at Keokuk. The record of the power used and its cost are shown in Table 12.

TABLE 12.—*Power used by Green Bay drainage pumping plant, 1919 to 1930*

Year	Amount of power		Cost of power		
	Kilowatt-hours	Per cent of average	Total	Per kilowatt-hour	Per acre assessed
			Dollars	*Cents*	*Dollars*
1918	[1] 392,850				
1919	[2] 867,930	102	9,009.42	1 04	1 02
1920	743,910	88	8,454.72	1.14	.96
1921	775,050	91	8,622.85	1.11	.98
1922	734,090	86	8,401.69	1.14	.95
1923	520,560	61	7,248.62	1.39	.82
1924	679,494	80	8,616.85	1.27	.98
1925	578,090	68	7,559.28	1.31	.86
1926	1,345,869	158	12,621.81	.94	1.43
1927	1,417,070	167	12,884.78	.91	1.46
1928	819,540	96	8,863.11	1.08	1.01
1929	976,230	115	9,512.47	.97	1.08
1930	[3] 315,970	37	3,603.50	1.14	.41
Average [4]	849,896	100	9,165.14	1.08	1.04

[1] Not included in average because furnished free.
[2] 22,550 kilowatt-hours furnished free.
[3] To July 1 only.
[4] Average for 11½ years.

The power consumption in 1925 was 68 per cent of the 11½-year average, and in 1926 it was 158 per cent, because of the break in the diversion levee. The cost per kilowatt-hour was less than for any other electric plant studied, averaging 1.08 cents per kilowatt-hour. The maximum cost in 1923 was only 1.39 cents per kilowatt-hour under the same rate.

The total costs for 1925 and 1926 are given in Table 13. As the plant has obtained electric current at such a low rate, the cost of power was a much smaller portion of the total than it would have been under less favorable rates. The first cost of the plant was high because the site was surrounded by water during its construction, and quicksand was encountered in the foundation work. As a result of these conditions the fixed charges have been greater than the cost of current.

TABLE 13.—*Operating costs, including fixed charges, for Green Bay drainage pumping plant, 1925–1926*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925.....dollars..	11, 203	7, 558	1, 200	147	75	20	383	20, 586
1926.....do....	11, 203	12, 729	1, 627	214	100	195	494	[1] 26, 562
Per cent of 1925 total.....	54.4	36.7	5.8	0.7	0.4	0.1	1.9	100

[1] Diversion-levee break necessitated large amount of pumping.

HARTWELL DRAINAGE AND LEVEE DISTRICT

The Hartwell drainage and levee district, on the east side of the Illinois River, is approximately rectangular, 3 miles wide by 5 miles long. The elevation of the land in the district varies from 426 to 440 feet (Memphis datum). Formerly the district obtained gravity drainage by means of a sluiceway at the southwest corner of the district, but all run-off now is pumped.

The pump house is a substantial brick structure with the machinery resting on heavy concrete foundations, and contains the four pumping units described in Table 1. Units Nos. 1 to 3 were installed in the original plant in 1915. Each can be operated at 234, 260, and 314 revolutions per minute by changing the pulleys on the motor shafts. A special apparatus which supports the chain drive enables the operator to change pulleys in less than an hour without assistance.

Unit No. 4, which began operating in January, 1929, was installed to provide both additional capacity and a more efficient pump. It consists of two synchronous motors mounted on the same shaft driving a 48-inch centrifugal pump having a screw-type impeller. The high-speed motor which operates at 327 revolutions per minute is rated at 458 horsepower, and the low-speed motor operating at 240 revolutions per minute is rated at 200 horsepower. This unit was unusually well designed to operate efficiently against variable lifts.

OPERATION OF PLANT

Daily operation records were kept during 1929 and 1930, and the monthly summary figures are given in Table 14. The run-off from this district was 20.27 inches during 1929, but only 7.23 inches in 1930, and for both years it was much below the average for the Illinois River plants studied. The small monthly run-off at low lifts indicates that there is little seepage into the district at low-river stages. The consumption of power per acre-foot of water was unusually small in comparison to that at other plants, especially at low lifts. This high efficiency was obtained by operating the screw pump at low speed, which during tests gave better efficiencies below 10-foot lift than any other electric-driven unit.

TABLE 14.—*Monthly operations of Hartwell drainage pumping plant, 1929 and 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity							
1929	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*	*Indicated horsepower-hours*	*Brake horsepower-hours* [1]	*Per cent*	*Per cent*
January	3.52	1.63	1,752	7.78	61,870	34,550	26.5	24.3	40	69
February	.64	.80	860	8.18	21,500	13,890	21.7	20.2	52	81
March	6.45	3.10	3,336	14.58	128,860	89,210	35.9	33.2	56	86
April	4.24	2.63	2,823	18.13	117,760	81,970	38.9	36.2	64	87
May	9.94	5.11	5,497	15.77	233,570	176,400	43.0	39.7	50	94
June	4.43	2.28	2,452	11.90	92,270	52,460	28.7	26.6	57	71
July	5.21	1.76	1,890	11.41	67,610	44,480	31.6	29.2	50	82
August	2.77	.52	565	4.81	15,210	9,090	21.6	20.0	31	74
September	3.28	.32	342	3.67	15,850	7,050	27.6	25.1	18	54
October	5.29	.72	779	4.58	23,770	10,150	17.5	16.1	36	53
November	1.65	.89	951	4.74	24,910	14,070	19.8	18.4	33	70
December	.84	.51	549	3.76	16,110	9,340	22.8	21.1	23	72
Total or average	48.26	20.27	21,796	12.48	819,290	542,660	33.4	30.9	51	82
1930										
January	3.37	1.79	1,919	7.53	59,060	32,070	22.4	20.6	46.1	66.8
February	1.82	2.53	2,716	10.89	90,240	59,910	29.6	27.1	50.6	81.6
March	1.25	1.36	1,462	11.28	42,990	29,760	27.3	25.1	56.7	85.5
April	1.16	.65	698	8.06	17,300	10,670	20.5	18.9	53.9	76.4
May	1.19	.49	530	8.88	15,210	8,400	21.2	19.6	57.4	68.2
June	3.82	.28	298	3.74	9,840	4,980	22.4	20.4	22.9	61.8
July	.32	.00								
August	.75	.00								
September	4.11	.02	23	1.39	1,050	540	31.3	28.3	6.1	61.9
October	2.07	.02	19	1.58	800	390	27.4	24.7	7.9	58.8
November	2.87	.00								
December	.60	.09	94	1.34	4,350	2,270	32.3	29.1	5.7	63.0
Total or average	23.33	7.23	7,759	9.30	240,840	148,990	25.7	23.6	49.6	76.2

[1] Motor efficiencies assumed as 90.7 to 93.0 per cent.

COST OF PUMPING

The monthly rate paid for electric current during 1929 and 1930 known as the standard day rate, was as follows: First 8,800 kilowatt-hours at 5 cents, next 17,600 kilowatt-hours at 3.5 cents, and additional kilowatt-hours at 2.3 cents. Discounts and other conditions were the same as those given for the Banner Special plant for 1926 and 1927 (p. 17). The minimum annual charge was $10 per horsepower of the total horsepower in normal ratings of the motors driving the pumps, until June 15, 1929, at which time it was reduced to $8 per horsepower. This charge for 1930 was based on a rating of 758 horsepower.

The record of power consumption from 1916 to 1930 is given in Table 15. The years 1926 to 1929 were unusually wet, and the power consumption ranged from 133 to 207 per cent of the 15-year average. The only year previous to 1926 when the power consumption was above the 14-year average was 1920. The power rates have shown a decrease since 1921, when the cost was 4.22 cents per kilowatt-hour. In 1930, on account of the small consumption, the cost of power was the total minimum annual charge, which amounted to 4.07 cents per kilowatt-hour. At the kilowatt-hour rates, the cost of the current actually used would have been $3,859.

The operating costs for 1929 and 1930 are shown in Table 16.

TABLE 15.—*Power used by Hartwell drainage pumping plant, 1916 to 1930*

Year	Amount of power		Cost of power		
	Kilowatt-hours	Per cent of average	Total	Per kilowatt-hour	Per acre assessed
			Dollars	*Cents*	*Dollars*
1916	229,560	83	5,950.78	2.59	0.67
1917	187,820	68	4,820.47	2.57	.54
1918	113,600	41	3,499.26	3.08	.39
1919	197,330	71	5,838.45	2.96	.66
1920	293,490	106	7,755.32	2.64	.87
1921	211,190	76	8,912.22	4.22	1.00
1922	237,200	86	6,724.75	2.84	.76
1923	176,260	64	5,236.08	2.97	.59
1924	254,700	92	7,718.94	3.03	.87
1925	213,550	77	6,889.56	3.23	.77
1926	398,020	144	9,135.13	2.30	1.03
1927	570,680	207	11,788.38	2.07	1.32
1928	367,400	133	9,114.50	2.48	1.02
1929	542,660	196	10,790.72	1.99	1.21
1930	148,990	54	6,064.00	4.07	.68
Average	276,163	100	7,349.24	2.66	.83

TABLE 16.—*Operating costs, including fixed charges, for Hartwell drainage pumping plant, 1929 and 1930*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1929 dollars	6,470	10,791	1,464	41	43	72	583	19,464
1930 do	6,470	6,064	1,500	254	69	55	314	14,726
Average do	6,470	8,427	1,482	148	56	64	448	17,095
Per cent of total	37.8	49.3	8.7	0.9	0.3	0.4	2.6	100

HUNT DRAINAGE AND LEVEE DISTRICT

The Hunt drainage and levee district, on the east side of the Mississippi River, is nearly 10 miles long and 4 miles wide at the lower end. The Lima Lake and the Hunt districts are inclosed within the same river levee, and are separated only by a solid spoil bank. About 2,000 acres lying in the Hunt district are drained by the Lima Lake plant. The enterprise was organized as a levee district in 1880; the diversion of the hill streams and the construction of the pumping plant and interior ditch system were begun in 1927. The pumping plant began operating in April, 1928.

The building is very substantial and has a steel frame and stucco walls. It was constructed for three pumping units but only the two described in Table 1 were installed. Pump No. 1 is suspended on steel I-beams over the suction bay, the long suction pipe being thus eliminated. The pump is driven by two synchronous motors, mounted on the same shaft, which are operated at speeds of 257 and 225 revolutions per minute. The great advantage of this type of installation is that the speed of the pump can be changed on the operating board without changing pulleys or gears. The disadvantage of the low starting torque ordinarily developed by synchronous motors had been overcome in the drainage plants using them by

special design. Unit No. 2 consists of an induction motor operating at 435 revolutions per minute, direct-connected to a centrifugal pump containing a screw-type impeller. Both units were among the first of their type installed in a drainage plant in the upper Mississippi Valley.

OPERATION OF PLANT

Daily operation records were kept during 1928 to 1930, and the monthly summaries are given in Table 17. During the first two years, before the diversion ditch was completed, water flowed in from the hill areas, and water from Lima Lake also was pumped. These conditions are not typical of those that obtained during 1930 after Lima Lake was completely drained.

TABLE 17.—*Monthly operations of Hunt drainage pumping plant, 1928 to 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity				*Indicated horsepower hours*	*Brake horsepower-hours* [1]		
1928	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
April [2]	0.55	1.34	1,774	8.66	60,560	39,850	30.1	27.8	40	81
May	3.69	2.81	3,709	8.26	137,140	81,800	29.6	27.3	38	74
June	4.38	1.60	2,118	8.41	75,020	41,340	26.2	24.3	44	68
July	2.88	.86	1,131	8.92	39,800	24,410	28.9	26.7	42	76
August	3.07	.39	515	8.51	17,480	11,100	28.9	26.4	40	78
September	4.15	.10	128	8.52	4,380	2,830	29.7	27.2	39	80
October	6.16	2.43	3,204	8.24	109,290	65,710	27.5	25.2	41	74
November	6.07	5.46	7,205	6.76	238,150	142,800	26.6	24.3	35	74
December	1.73	1.65	2,180	6.03	71,160	41,790	25.7	23.5	32	72
Total or average	32.68	16.64	21,964	7.63	752,980	451,630	27.6	25.4	38	74
1929										
January	2.67	.00								
February	.86	.11	150	2.51	4,560	2,600	23.3	21.1	15	69
March	4.55	2.42	3,193	12.75	121,710	84,840	35.6	32.6	49	86
April	6.95	7.35	9,699	12.43	356,580	233,140	32.2	29.5	53	80
May	3.58	4.34	5,729	10.11	202,210	123,770	29.0	26.5	48	75
June	5.01	3.39	4,481	6.76	148,590	85,070	25.5	23.3	36	70
July	6.92	3.43	4,522	5.83	148,510	86,300	25.6	23.4	31	71
August	1.74	.39	514	4.92	16,500	9,900	25.8	23.6	26	74
September	3.08	.12	160	6.23	5,250	3,200	26.8	24.6	32	75
October	5.09	.32	423	5.53	14,070	8,200	26.0	23.9	29	72
November	1.56	.57	757	6.05	25,400	15,600	27.6	25.4	30	76
December	1.11	.26	343	5.59	11,230	6,600	25.8	23.6	30	72
Total or average	43.12	22.70	29,971	9.63	1,054,610	659,220	29.5	27.0	45	77
1930										
January	2.31	.00								
February	1.98	1.01	1,327	5.59	43,940	28,600	28.9	26.6	26.6	80.4
March	1.06	1.33	1,757	6.14	58,460	34,100	26.0	24.0	32.4	72.0
April	2.71	.71	932	6.28	30,380	16,200	23.3	21.2	37.0	65.1
May	2.18	.74	971	6.56	31,010	19,300	26.7	24.2	33.8	75.7
June	3.34	.65	853	8.30	27,760	18,500	29.1	26.4	39.2	81.0
July	.09	.29	378	6.69	11,990	7,500	26.6	24.1	34.5	76.0
August	.97	.00								
September	3.62	.00								
October	2.48	.00								
November	3.37	.00								
December	.63	.00								
Total or average	24.74	4.73	6,218	6.44	203,540	124,200	26.8	24.5	33.0	74.8

[1] Motor efficiencies assumed as 90.5 to 92.7 per cent.
[2] Records commenced Apr. 18.

COST OF PUMPING

The district was billed on the off-peak rate (p. 21). The monthly primary charge was based on 450 horsepower until June 1, 1930, when 200 horsepower was sealed off. The actual cost of power has averaged more on the off-peak rate than it would have on the optional standard day rate (p. 17) although there was a saving in 1928, as shown by Table 18. The district apparently could have saved materially by using the standard day rate during these first three years the plant operated. The off-peak rate would be more advantageous if the district pumped more frequently during dry months to hold the suction bay at a lower stage.

TABLE 18.—*Comparison of costs of power under off-peak and standard day rates, for Hunt drainage and levee district*

Year	Power used	Actual cost on off-peak rate		Estimated cost on standard day rate		Estimated loss due to pumping off peak
		Total	Per kilowatt-hour	Total	Per kilowatt-hour	
	Kilowatt-hours	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*
1928	451,630	9,150	2.03	9,351	2.07	[1] 201
1929	659,220	12,614	1.91	11,845	1.80	769
1930	124,100	4,748	3.83	3,750	3.02	998
Total						1,566

[1] Profit.

TABLE 19.—*Operating costs, including fixed charges, for Hunt drainage pumping plant, 1928 to 1930*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1928 dollars	4,815	9,150	1,013	95	69	27	910	[1] 16,079
1929 do	6,830	12,614	1,499	174	75	58	1,275	22,525
1930 do	6,830	4,748	1,200	502	47	13	1,034	14,374
Average do	6,830	9,801	1,372	285	71	36	1,160	19,585
Per cent of total	34.9	50.0	7.0	1.4	0.4	0.2	6.1	100.0

[1] For period Apr. 18, to Dec. 31, 1928.

Table 19 gives the operating costs for the first three years of the plant's operation. The fixed charges are quite high, because of the high first cost. The contract price was $69,000. Contract bids of $79,540, $87,450, and $89,880 had been received for alternate oil-engine installations.

INDIAN GRAVE DRAINAGE AND LEVEE DISTRICT

The Indian Grave drainage and levee district, on the east side of the Mississippi River, is separated from the Lima Lake district by the Bear Creek floodway. The district was organized about 1880, with a gravity outlet. The present pumping plant and other drainage im-

provements were constructed in 1917 and 1918. In 1920 the levee broke at the pumping plant and destroyed the east end of the build-

FIGURE 3.—Exterior view of Indian Grave drainage pumping plant showing high quality of building and long trash screen in suction bay

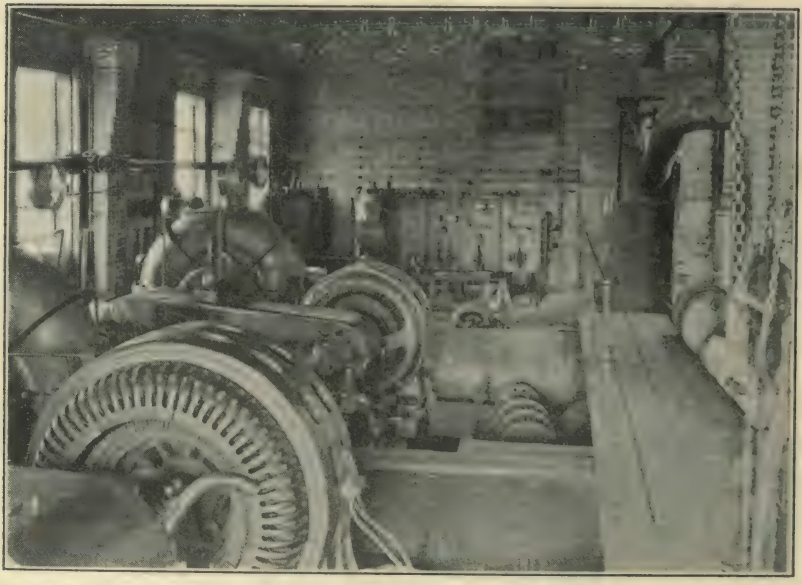


FIGURE 4.—Interior view of Indian Grave pumping plant showing electric motors chain-connected to pumps, and typical switchboard

ing. In repairing the plant, the gravity outlet through the levee was removed, and subsequently all run-off has been pumped. Rock Creek is carried across the district between two levees, and an inverted

syphon under the channel carries the drainage water from the upper to the lower half of the district.

The pump house is a 3-story brick structure with concrete foundations, the upper story being used as the plant operator's residence. Figure 3 shows an exterior view and Figure 4 an interior view of the plant. The three pumping units are described in Table 1. Pumps No. 2 and No. 3 are connected to one 400-horsepower induction motor. They were operated at approximately 355 revolutions per minute until the latter part of 1927, when new impellers were installed and the speed reduced to 295 revolutions per minute. Pump No. 1 has been operated at but one speed, 355 revolutions per minute.

OPERATION OF PLANT

The operation data for this plant during 1925 to 1930, inclusive, are shown in Table 20. The amount of pumping was very small during 1925 and 1930, quite large in 1926 and 1927, and average in 1928. In March, 1929, the main river levee broke in two places and the entire district was flooded. After the flood water receded, the motors and transformers were dried out and pumping was resumed in November, 1929. The stages of the discharge bay were not much higher than those of the suction bay, during low stages of the river.

The capacity of the plant is not considered sufficient to handle the run-off under most adverse conditions. During some floods water in the suction bay rose 3 and even 4 feet above the optimum stage. The maximum 24-hour run-off pumped was 0.269 inch.

TABLE 20.—*Monthly operations of Indian Grave drainage pumping plant, 1925 to 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used [1]	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity				*Indicated horsepower-hours* [2]	*Brake horsepower-hours* [3]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
January	0.33	0.17	301	0.70	9,700	8,180	35.7	33.2	3	103
February	1.90	.63	1,111	.90	35,560	29,900	35.4	32.9	4	103
March	1.93	.87	1,530	1.22	42,260	36,100	31.0	28.8	5	104
April	2.63	.64	1,128	1.01	31,090	25,500	29.7	27.6	5	100
May	2.12	.48	839	.75	22,940	19,500	30.5	28.4	3	104
June	4.58	.41	711	4.49	21,510	18,500	34.2	31.8	18	105
July	3.93	.57	996	2.64	27,910	24,200	31.9	29.7	11	106
August	5.03	.35	611	1.83	16,780	13,800	29.7	27.6	8	100
September	4.52	.26	457	1.28	13,260	10,600	30.5	28.3	6	98
October	3.28	.72	1,265	1.34	36,660	30,800	32.0	29.8	6	103
November	2.02	.90	1,575	1.14	45,680	40,200	33.5	31.2	5	108
December	1.36	1.07	1,864	.75	53,320	47,100	33.2	30.9	3	108
Total or average	33.63	7.07	12,388	1.39	356,670	304,380	32.3	30.0	6	104
1926										
January	.82	.85	1,494	2.00	44,150	39,200	34.5	31.9	8	108
February	1.83	1.02	1,789	1.37	53,510	45,800	33.6	31.2	6	104
March	1.51	1.03	1,795	1.72	52,860	44,500	32.6	30.2	7	103
April	2.14	1.78	3,118	3.94	93,030	77,200	32.5	30.2	17	101
May	2.21	.79	1,391	2.31	39,090	32,400	30.6	28.4	10	101
June	6.22	1.48	2,589	3.54	73,670	63,000	32.0	29.6	15	104

[1] Meter on primary side of transformer.
[2] Transformer efficiencies assumed as 98 per cent.
[3] Motor efficiencies assumed as 83.2 to 93.0 per cent.

TABLE 20.—*Monthly operations of Indian Grave drainage pumping plant, 1925 to 1930*—Continued

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours	Overall efficiency	Average load on motors
1926	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
July	1.62	.48	836	1.15	23,560	19,600	30.8	28.6	5	102
August	4.09	.30	532	1.43	14,760	12,100	29.9	27.7	7	100
September	11.72	3.18	5,566	6.60	172,900	150,800	35.6	33.0	26	106
October	3.99	3.92	6,859	7.15	216,540	198,900	38.1	35.0	26	111
November	2.46	1.70	2,969	2.95	88,210	78,000	34.5	31.6	12	106
December	.95	1.30	2,273	2.18	67,190	59,100	34.2	31.4	9	106
Total or average	39.56	17.83	31,211	4.31	939,470	820,600	34.6	31.9	17	106
1927										
January	1.58	.65	1,136	1.20	32,510	26,000	30.1	27.7	6	97
February	1.91	1.54	2,688	3.69	80,340	72,800	35.6	32.6	14	109
March	4.01	2.41	4,225	5.00	128,430	115,410	35.9	33.0	19	108
April	5.25	5.07	8,866	9.49	292,890	273,590	40.6	37.1	32	112
May	4.81	3.34	5,839	8.50	181,140	163,300	36.8	33.7	32	109
June	4.48	3.29	5,760	7.92	180,480	162,500	37.1	34.0	29	108
July	2.01	.71	1,237	2.17	34,380	27,300	29.0	26.7	10	96
August	1.94	.36	637	1.24	17,530	14,300	29.5	27.2	6	99
September	2.60	.24	419	1.62	11,590	9,700	30.4	28.0	7	101
October	4.34	.67	1,172	4.74	34,630	32,603	36.6	32.9	18	111
November	3.22	.57	1,002	1.36	29,790	18,300	24.0	22.1	8	74
December	2.95	.65	1,140	1.36	33,930	20,500	23.6	21.8	8	73
Total or average	39.10	19.50	34,121	6.58	1,057,640	936,303	36.1	33.1	25	107
1928										
January	.28	1.09	1,910	2.67	58,760	33,600	23.1	21.3	16	69
February	1.83	1.40	2,449	3.39	77,810	40,400	21.7	20.1	22	63
March	.84	.82	1,438	4.30	46,360	24,400	22.3	20.7	26	64
April	3.57	2.04	3,563	8.45	121,810	77,800	28.7	26.4	40	77
May	1.94	1.57	2,756	5.66	90,130	50,600	24.1	22.3	32	68
June	6.15	1.00	1,746	2.24	54,390	27,600	20.8	19.3	15	62
July	2.40	.69	1,204	3.12	38,130	19,300	21.1	19.6	20	62
August	3.50	.46	799	3.29	25,470	12,800	21.1	19.6	22	61
September	3.55	.47	826	4.57	26,890	16,228	25.8	24.0	24	74
October	5.97	1.02	1,781	4.75	57,810	30,900	22.8	21.2	29	65
November	5.17	3.53	6,184	6.75	203,380	127,700	27.1	24.9	34	76
December	1.35	1.79	3,133	3.97	98,780	53,800	22.6	20.8	24	66
Total or average	36.55	15.88	27,789	5.11	899,720	515,128	24.4	22.5	29	69
1929										
January	4.08	1.60	2,798	1.31	84,990	43,700	20.5	19.0	9	63
February	.85	1.54	2,696	4.54	86,270	47,200	23.0	21.3	27	66
March [1]	3.70	2.74	4,789	9.13	166,230	108,900	29.9	27.5	42	79
November	.13	.01	19	------	500	700	48.4	43.2	------	164
December	.75	.75	1,314	.19	34,880	31,917	31.9	28.7	1	108
Total or average	9.51	6.64	11,616	5.15	372,870	232,417	26.3	24.2	27	75
1930										
January	3.31	.68	1,191	.45	31,320	28,190	31.1	25.9	2	98
February	.74	1.47	2,566	1.85	79,110	38,591	19.8	18.1	13	59
March	1.23	1.37	2,404	3.55	76,900	39,487	21.6	19.2	23	60
April	.70	.67	1,172	2.14	36,610	19,563	21.9	20.0	13	64
May	.82	.52	901	2.79	28,430	14,923	21.8	19.9	18	63
June	4.16	.65	1,134	6.81	38,880	21,399	24.8	22.6	38	66
July	.36	.24	422	3.16	12,900	8,247	25.7	23.0	17	75
August	1.55	------	------	------	------	------	------	------	------	------
September	2.16	------	------	------	------	------	------	------	------	------
October	2.18	------	------	------	------	------	------	------	------	------
November	4.76	------	------	------	------	------	------	------	------	------
December	.36	------	------	------	------	------	------	------	------	------
Total or average	22.33	5.60	9,790	2.85	304,150	170,400	22.9	20.5	17	66

[1] Plant flooded Mar. 21 ;pumping resumed Nov. 19.

COST OF PUMPING

The cost of current included the transformer losses, as the meters were set on the primary side of the transformers. This is not customary practice, but the charge for current is unusually low. The cost of power supplied to the district has comprised a demand or investment charge of $4.50 per year per horsepower of maximum demand and service charges as follows: First 1,000 kilowatt-hours at 2 cents, next 1,000 kilowatt-hours at 1.5 cents, next 14,000 kilowatt-hours at 0.75 cent, and additional kilowatt-hours at 0.54 cent. The demand was based on the highest demand meter reading during the preceding 12 months, and was billed in equal monthly installments. No discount was allowed. The service rates applied only to "off-peak" consumption, which was limited to 13 hours per day on Mondays to Fridays, 19 hours on Saturdays, and 24 hours on Sundays and holidays. A charge of $50 was made for each day that these limits were exceeded.

The cost of power used by the Indian Grave plant from 1918 to 1930 is shown in Table 21. The cost per assessed acre has been less for this district than for any other studied. The average cost per kilowatt-hour has been less than that for any plant except the Green Bay. The average consumption of current during 1925 to 1930, excepting 1929, was 549,362 kilowatt-hours, or 23 per cent above the 13-year average. If the flooding of the plant had not prevented pumping for several months in 1929, probably the consumption of power in that year would have been even greater than that during 1927.

TABLE 21.—*Power used by Indian Grave drainage pumping plant, 1918–1930*

Year	Amount of power		Cost of power		
	Kilowatt-hours	Per cent of average	Total	Per kilowatt-hour	Per acre assessed
			Dollars	*Cents*	*Cents*
1918 [1]	114,933	26	1,386.98	1.21	8
1919	536,119	120	6,328.92	1.18	35
1920	809,778	181	9,749.97	1.20	53
1921	321,170	72	4,891.32	1.52	27
1922	546,200	122	6,722.34	1.23	37
1923	198,700	44	4,914.32	2.47	27
1924	317,058	71	5,737.31	1.81	31
1925	306,380	68	5,681.04	1.85	31
1926	817,400	182	8,206.87	1.00	45
1927	937,203	209	9,552.43	1.02	52
1928	514,728	115	6,763.00	1.31	37
1929	232,717	52	2,695.81	1.16	15
1930	169,900	38	2,941.35	1.73	16
Average	447,868	100	5,813.20	1.30	32

[1] Pumping commenced in April, 1918.

The early tests revealed that these pumps had been designed for a much higher lift than necessary, that the impellers were badly worn, and that the efficiencies were extremely low. New impellers were installed in pumps Nos. 2 and 3 in 1927, and the speeds were reduced from 355 to 295 revolutions per minute, which improved the efficien-

cies about 30 per cent. Figure 5 shows worn condition of the old impeller and Figure 6 the type of new impeller installed.

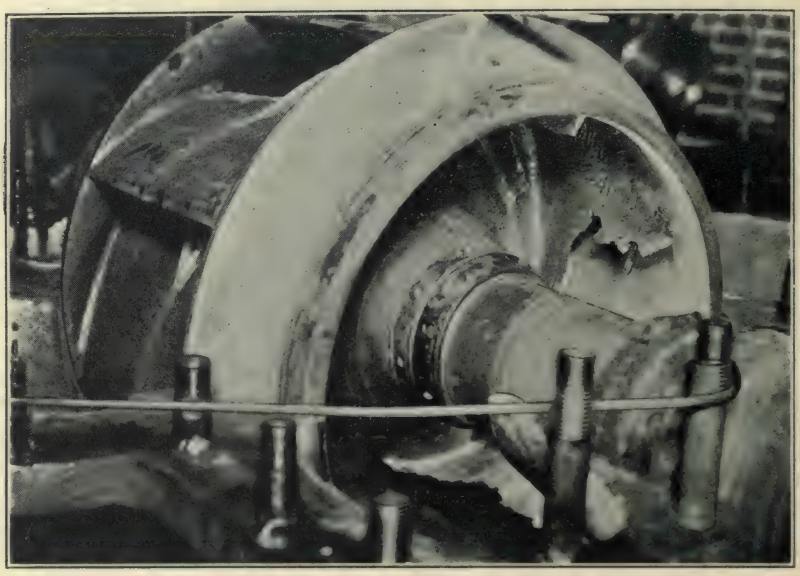


FIGURE 5.—Worn impeller discarded from drainage pump in Indian Grave plant

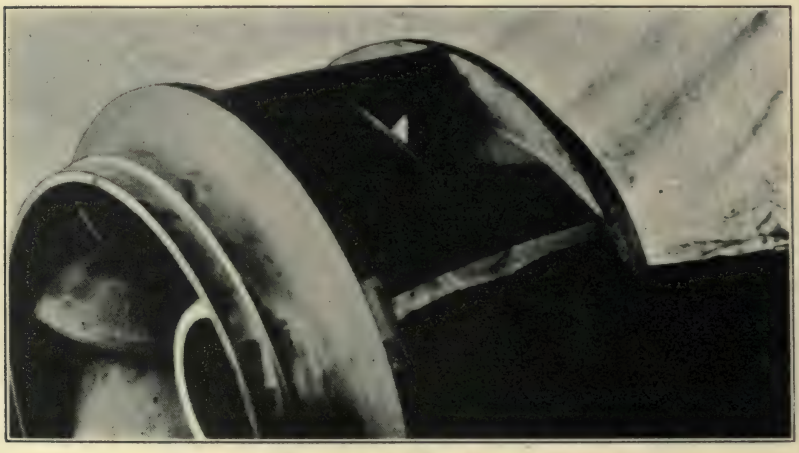


FIGURE 6.—New impeller installed in Indian Grave pump

The operating costs are given in Table 22. The repairs include $2,576 in 1927 for replacement of the two impellers and $665 in 1928 for repairing motor coils. The large repairs necessary in 1929 were the result of the flooding of the plant.

TABLE 22.—*Operating costs, including fixed charges, for Indian Grave drainage pumping plant, 1925–1930*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 dollars	7,154	5,681	1,200	75	125	195	486	14,916
1926 do	7,154	8,207	1,200	131	200	256	612	17,760
1927 do	7,154	9,552	1,500	2,838	340	173	1,044	22,601
1928 do	7,154	6,763	1,500	886	280	213	804	17,600
1929 [1] do	7,154	2,696	1,466	3,624	143	195	879	16,157
1930 do	7,154	2,941	1,225	500	51	310	414	12,595
Average for five years do	7,154	6,629	1,325	886	199	229	672	17,094
Per cent of total	41.8	38.8	7.8	5.2	1.2	1.3	3.9	100

[1] Plant flooded Mar. 21; pumping resumed Nov. 19, 1929. Costs for 1929 omitted from averages.

The improved plant efficiency due to installing new impellers in 1927 and reducing the speed, as described, enabled the district to save more than the cost of these repairs in the first three years. The average consumption of power per acre-foot pumped during 1928 to 1930 was 18.7 kilowatt-hours, or 7.8 kilowatt-hours less than during 1925 to 1927, at practically equal lifts. The quantity pumped in 1928 to 1930 was 49,195 acre-feet, for which the saving in power was approximately 383,700 kilowatt-hours, estimated at the above rate. The saving in cost, at 0.54 cent per kilowatt-hour, would amount to $2,072. Also, the maximum demand was reduced slightly over 200 horsepower, which resulted in a further saving of $900 per year or, for the actual period of pumping in 1928 to 1930, something in excess of $2,100. This total saving of approximately $4,200 in the three years exceeded the cost of the new impellers and sprockets by at least $1,600.

LIMA LAKE DRAINAGE AND LEVEE DISTRICT

The Lima Lake drainage and levee district, on the east side of the Mississippi River, is approximately 4 miles wide and 5 miles long and is inclosed within the same river levee as the Hunt district. Only the higher lands along the bluff and along the river have been cultivated. The bed of a shallow lake comprises a large part of the area. The diversion of the hill streams and the construction of the pumping plant and drainage ditches were begun in 1927. The pumping plant is located on Bear Creek about 2½ miles from the Mississippi.

The building is very substantial, having a steel frame and stucco walls. The three pumping units are described in Table 1. Pumps No. 1 and No. 3 are of the bottom-suction type, and are suspended on steel beams over the suction bay, which results in short suction pipes. Pump No. 1 is driven by two synchronous motors mounted on the same shaft, which operate at speeds of 240 and 277 revolutions per minute, and is similar to unit No. 1 of the Hunt plant. Pump No. 3 is direct connected to an induction motor which operates at 273 revolutions per minute. Unit No. 2 consists of an induction motor operating at 435 revolutions per minute, direct connected to a centrifugal pump containing a screw-type impeller of the same design as unit No. 2 of the Hunt plant.

OPERATION OF PLANT

The plant began operating in November, 1928, but shortly afterwards the Bear Creek levee broke, and the plant was flooded for a few days. Daily records were begun January 1, 1929.

The operation records are given in Table 23. The high lifts shown for January, February, and June, 1929, were caused by the end of the discharge pipe being out of water; the elevation of the water in the top of the discharge pipe therefore, instead of in the discharge bay, was used in computing the static lift. The discharge pipes were completed during the summer, and the static lift decreased during the latter half of the year.

TABLE 23.—*Monthly operations of Lima Lake drainage pumping plant, 1920 and 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity				*Indicated horsepower hours*	*Brake horsepower-hours* [1]		
1929	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
January	2.67	4.17	5,788	18.87	229,520	165,820	38.4	35.0	67	88
February	.86	1.90	2,628	15.50	161,100	88,210	45.0	41.0	47	67
March	4.55	5.90	8,175	11.18	307,750	232,070	38.1	34.6	40	92
April	6.95	9.95	13,797	11.56	480,890	358,590	34.9	31.7	46	91
May	3.58	9.79	13,578	8.40	458,590	327,900	32.4	29.5	36	87
June	5.01	1.27	1,756	10.21	76,460	43,700	33.4	30.4	42	70
July	6.92	1.23	1,707	8.53	68,370	39,200	30.8	28.0	38	70
August	1.74	4.58	6,351	3.91	216,540	112,100	23.7	21.5	23	63
September	3.08	.40	552	5.01	17,230	9,500	23.1	21.0	30	67
October	5.09	1.55	2,156	6.71	69,840	31,300	19.5	17.7	47	55
November	1.56	1.48	2,057	7.09	65,940	35,200	22.9	20.9	42	65
December	1.11	.69	959	6.28	30,390	17,500	24.5	22.3	35	70
Total or average	43.12	42.91	59,504	10.25	2,182,620	1,461,090	32.9	30.0	43	82
1930										
January	2.81	.48	667	6.83	21,250	12,500	25.1	22.9	37	72
February	.81	2.08	2,883	9.46	88,250	78,400	36.5	33.2	36	108
March	1.15	2.23	3,099	7.63	95,060	52,100	22.5	20.5	46	67
April	1.72	1.04	1,445	6.98	46,140	29,000	26.9	24.5	36	77
May	2.64	1.25	1,731	7.70	55,360	36,300	28.1	25.6	38	80
June	5.01	.96	1,327	10.66	42,750	33,000	33.3	30.3	44	94
July	.22	.68	941	8.05	30,210	16,700	23.8	21.6	46	67
August	1.12	.22	304	5.92	9,560	6,600	29.1	26.5	28	84
September	2.43	.20	281	6.65	8,940	6,000	28.6	26.1	32	82
October	2.57	.26	355	6.96	11,330	6,300	23.8	21.7	40	68
November	3.97	.21	295	6.63	9,380	6,200	28.2	25.6	32	81
December	.63	.60	835	6.77	26,560	16,000	25.7	23.4	36	73
Total or average	25.08	10.21	14,163	8.07	444,790	299,100	28.3	25.8	39	82

[1] Motor efficiencies assumed as 91 per cent.

As the ditch system was not complete, the ditch stages were higher than they will be when the project is completed. During the first few months water from hill areas flowed into the district because the diversion levee was not completed. In view of these abnormal conditions, the records obtained during 1929 are not considered typical for this district. The amount of pumping necessary during 1930 was no doubt less than the average will be.

COST OF PUMPING

The power used by the district was billed on the off-peak rate (p. 21). The connected load varied during 1929 from 450 horsepower when unit No. 1 was operated at low speed together with one of the other units, to 700 horsepower when all units were operated simultaneously. The connected load was 450 during the first half of 1930, but unit No. 1 was sealed off on July 1, which reduced the connected load to 250 horsepower, and unit No. 2 did all the pumping for the remainder of the year.

The plant consumed 157,470 kilowatt-hours during November and December, 1928, which cost $2,532. During 1929 1,465,760 kilowatt-hours were billed, costing $23,721 or 1.62 cents per kilowatt-hour. Since the district was being drained and abnormal flood conditions obtained during the spring months of 1929, the amount of pumping done during off-peak hours was only 44 per cent of the total; yet the actual cost was $246, or 1 per cent, less than the estimated cost had the district operated on the optional day rate.

The power consumption during 1930 was 298,400 kilowatt-hours, of which only 20,000 kilowatt-hours, or 7 per cent, was consumed on the day rate. The actual cost was $1,575, or 20 per cent less than the estimated cost on the optional day rate.

The operating costs for 1929 and 1930 are given in Table 24. The cost of power was probably much greater than it will average when the district operates under normal conditions.

TABLE 24.—*Operating costs, including fixed charges, for Lima Lake drainage pumping plant, 1929 and 1930*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plants	Total
1929.....dollars..	8,308	23,721	1,429	214	125	113	1,170	35,080
1930.....do....	8,308	6,355	1,200	427	40	616	261	17,207
Average.....do....	8,308	15,038	1,315	321	82	364	716	26,144
Per cent of total.....	31.8	57.5	5.0	1.2	.3	1.4	2.8	100

SOUTH BEARDSTOWN DRAINAGE AND LEVEE DISTRICT

The South Beardstown drainage and levee district, on the east side of the Illinois River, is about 7¼ miles long and about 1¼ miles in average width. Nearly all the district was formerly covered by a shallow lake. The land lies unusually low with respect to river stages, and much of the surface is underlain by a stratum of sand at a depth of 3 to 6 feet. Because of this sand and the low ground elevation, there is a large amount of seepage to be pumped. The sand stratum, however, also provides very good underdrainage for much of the district when the water in the ditches is held low.

The pump house is a steel-frame building with stucco finish. The wall foundations are of concrete, and extend 4 feet above the ground surface to form the walls for the main structure. Provision was made to hold water out of the plant in the event of a flood. The four pumping units are described in Table 1. The pumps are of the bot-

tom-suction type, suspended over the suction bay similarly to those in the Hunt, Lima Lake, and Coal Creek plants. The 26-inch pump can be driven at speeds of 283, 310, and 325 revolutions per minute, and each of the three 30-inch pumps at 266, 293, and 308 revolutions per minute, by changing pulleys on the motor shaft.

OPERATION OF PLANT

The operation data for this plant during the period 1925 to 1930 are given in Table 25. The average run-off pumped from this district was larger than that pumped from any other district studied. In 1926 it exceeded the rainfall by 26 per cent, and for the entire 6-year period by 7 per cent. The run-off increased rapidly with the static lift, indicating that the river stage greatly affects the quantity of seepage. A dam in the river at La Grange holds the water above a stage of approximately 35 feet at the plant, which undoubtedly increases the seepage at low stages.

TABLE 25.—*Monthly operations of South Beardstown drainage pumping plant, 1925 to 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot		Overall efficiency	Average load on motors
		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours* [1]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
January	0.40	1.99	1,388	11.09	42,350	41,018	39.6	35.5	38	116
February	1.90	3.19	2,217	13.38	73,980	66,100	40.0	35.8	46	107
March	2.46	3.50	2,434	13.95	84,100	79,358	43.7	39.1	44	113
April	2.83	2.90	2,015	12.93	72,020	59,800	39.8	35.6	45	100
May	1.38	2.07	1,437	11.03	52,840	36,800	34.3	30.6	44	83
June	3.36	1.87	1,299	9.83	44,290	30,600	31.6	28.1	43	82
July	4.80	1.73	1,205	9.40	42,240	29,000	32.3	28.7	40	82
August	4.84	1.79	1,247	9.07	43,540	29,100	31.3	27.9	40	80
September	4.39	1.37	953	8.66	33,210	22,500	31.7	28.2	38	81
October	3.72	2.34	1,626	9.29	56,890	38,700	31.9	28.4	40	81
November	2.97	2.89	2,009	10.18	70,480	47,900	32.0	28.5	44	81
December	1.03	2.33	1,619	10.15	56,150	37,400	31.0	27.6	45	80
Total or average	34.08	27.97	19,449	11.14	672,090	518,276	35.7	31.9	43	92
1926										
January	1.37	1.94	1,347	10.40	49,390	33,400	33.3	29.6	43	81
February	1.95	2.44	1,698	11.32	63,530	42,600	33.6	29.9	46	80
March	1.73	3.11	2,162	14.28	75,900	69,100	42.9	38.3	46	109
April	4.13	5.56	3,871	17.39	151,780	130,100	45.1	40.3	53	103
May	1.80	2.34	2,324	14.20	88,590	68,100	39.3	35.1	50	92
June	5.60	3.86	2,685	13.56	97,380	75,800	37.9	33.8	49	93
July	2.89	2.21	1,541	11.12	57,090	39,900	34.7	30.9	44	83
August	3.80	2.00	1,393	10.35	51,180	33,700	32.4	28.9	44	79
September	10.78	7.89	5,488	18.60	201,580	183,000	44.7	40.0	57	109
October	3.97	11.10	7,718	21.57	312,180	258,700	44.9	40.2	66	99
November	3.92	6.25	4,351	17.70	154,780	136,100	41.9	37.5	58	105
December	1.66	5.33	3,710	17.98	131,830	116,700	42.2	37.7	58	106
Total or average	43.60	55.03	38,288	16.84	1,435,210	1,187,200	41.6	37.1	56	99
1927										
January	1.42	2.92	2,035	12.94	67,650	53,900	35.5	31.7	50	95
February	1.58	4.35	3,026	17.76	111,970	94,600	41.9	37.5	58	101
March	6.53	6.98	4,856	17.69	173,640	149,600	41.3	36.9	59	103
April	7.42	9.67	6,728	21.37	275,580	233,200	46.5	41.6	63	101
May	7.68	8.64	6,014	20.68	241,170	199,900	44.6	39.8	64	99
June	3.80	6.99	4,861	22.13	205,360	172,400	47.6	42.5	64	101
July	2.34	2.99	2,078	12.83	68,560	54,500	35.2	31.4	50	95
August	2.75	2.12	1,475	9.93	50,120	34,500	31.4	27.9	44	82
September	3.60	1.77	1,229	9.99	42,730	26,900	29.3	26.1	47	75
October	4.12	4.04	2,814	15.13	100,020	77,500	36.9	32.9	56	93

[1] Motor efficiencies assumed as 88.5 to 89.5 per cent.

TABLE 25.—*Monthly operations of South Beardstown drainage pumping plant, 1925 to 1930*—Continued

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Current used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours [1]	Overall efficiency	Average load on motors
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
November	3.37	2.76	1,923	12.61	62,820	51,500	35.9	32.1	48	98
December	2.58	3.98	2,766	17.51	98,770	86,800	42.1	37.6	57	105
Total or average	47.19	57.21	39,805	17.85	1,498,390	1,235,300	41.6	37.2	59	99
1928										
January	.42	3.68	2,563	15.63	84,900	78,100	40.9	36.5	52	110
February	1.41	3.36	2,340	15.93	79,300	70,300	40.3	36.0	54	106
March	1.05	2.67	1,857	13.90	59,950	52,000	37.5	33.5	51	104
April	3.37	3.46	2,407	15.38	85,330	66,400	37.0	33.0	57	93
May	2.96	2.83	1,971	13.04	73,110	46,800	31.8	28.2	56	76
June	6.15	2.88	2,002	11.33	72,760	45,500	30.5	27.0	51	74
July	4.75	2.72	1,896	13.17	63,360	50,100	35.4	31.6	51	94
August	4.81	2.66	1,854	11.18	59,910	46,800	33.9	30.2	45	93
September	4.32	1.76	1,228	9.55	37,810	30,500	33.3	29.7	39	96
October	3.46	2.61	1,814	9.80	58,190	41,800	30.9	27.5	44	86
November	3.43	3.05	2,122	11.61	71,560	53,100	33.6	29.9	48	89
December	2.85	3.31	2,302	13.48	77,200	60,500	35.2	31.4	52	94
Total or average	38.98	34.99	24,356	13.11	823,380	641,900	35.3	31.5	51	93
1929										
January	3.84	3.91	2,719	14.28	93,250	73,000	36.0	32.2	54	94
February	.64	2.73	1,902	14.14	61,670	53,800	37.9	33.9	51	104
March	3.18	5.78	4,023	18.69	150,060	124,800	41.6	37.1	62	100
April	4.91	6.17	4,290	20.59	172,300	140,700	44.0	39.3	64	98
May	5.11	5.97	4,152	19.36	158,960	131,900	42.6	38.0	62	99
June	3.70	3.90	2,716	16.21	94,360	77,200	38.1	34.0	58	98
July	6.90	4.58	3,189	17.07	116,430	89,900	37.8	33.8	62	92
August	3.06	2.04	1,420	11.23	45,230	37,300	35.2	31.5	44	99
September	1.98	1.39	970	9.98	30,660	23,500	32.5	29.0	42	92
October	3.96	1.90	1,321	10.32	41,770	32,400	32.9	29.4	43	93
November	1.91	2.50	1,740	10.84	55,290	43,500	33.5	29.9	44	94
December	1.07	2.00	1,394	10.99	44,360	35,400	34.1	30.4	44	96
Total or average	40.26	42.87	29,836	16.14	1,064,340	863,400	38.8	34.7	57	97
1930										
January	2.84	2.77	1,929	12.83	63,570	49,900	34.7	31.0	51	94
February	2.19	4.33	3,013	15.34	105,880	82,000	36.5	32.6	58	93
March	1.93	3.97	2,760	16.40	100,730	80,700	39.2	35.0	57	96
April	1.71	2.70	1,876	14.66	64,510	51,000	36.5	32.6	55	95
May	1.50	2.41	1,676	14.18	57,340	44,000	35.2	31.4	55	92
June	2.91	1.48	1,031	9.77	32,430	25,300	32.9	29.4	41	93
July	1.42	1.51	1,049	9.20	32,600	24,700	31.6	28.2	40	91
August	1.63	.71	493	8.25	15,030	11,900	32.4	28.9	35	95
September	2.62	.93	648	8.76	19,860	14,200	29.4	26.2	41	86
October	1.63	1.26	876	8.45	26,940	19,400	29.7	26.5	39	86
November	2.37	1.33	928	8.51	28,590	21,900	31.6	28.3	37	92
December	.25	1.41	978	9.17	29,860	24,100	33.0	29.5	38	97
Total or average	23.00	24.81	17,257	12.82	577,340	449,100	34.9	31.2	50	93

[1] Motor efficiences assumed as 88.5 to 89.5 per cent.

The South Beardstown plant apparently kept the water level in the suction bay under better control than any other plant studied. The water in the suction bay was held below the normal stage of about 27 feet, except twice during 1926 and twice during 1927. Then it reached stages of about 29 feet, but each time was pumped down to normal before damage occurred. Figure 7 shows the daily operation records for 1927. These records are an excellent example of the operating conditions of a plant having a high capacity when operating against extreme flood conditions. The short duration of the rises in the suction bay should be noted. The large capacity of the plant and its

dependability were responsible for the excellent drainage rendered the district.

The maximum run-off pumped by the plant in 24 hours was 0.572 inch, which was greater than that pumped by any other plant except

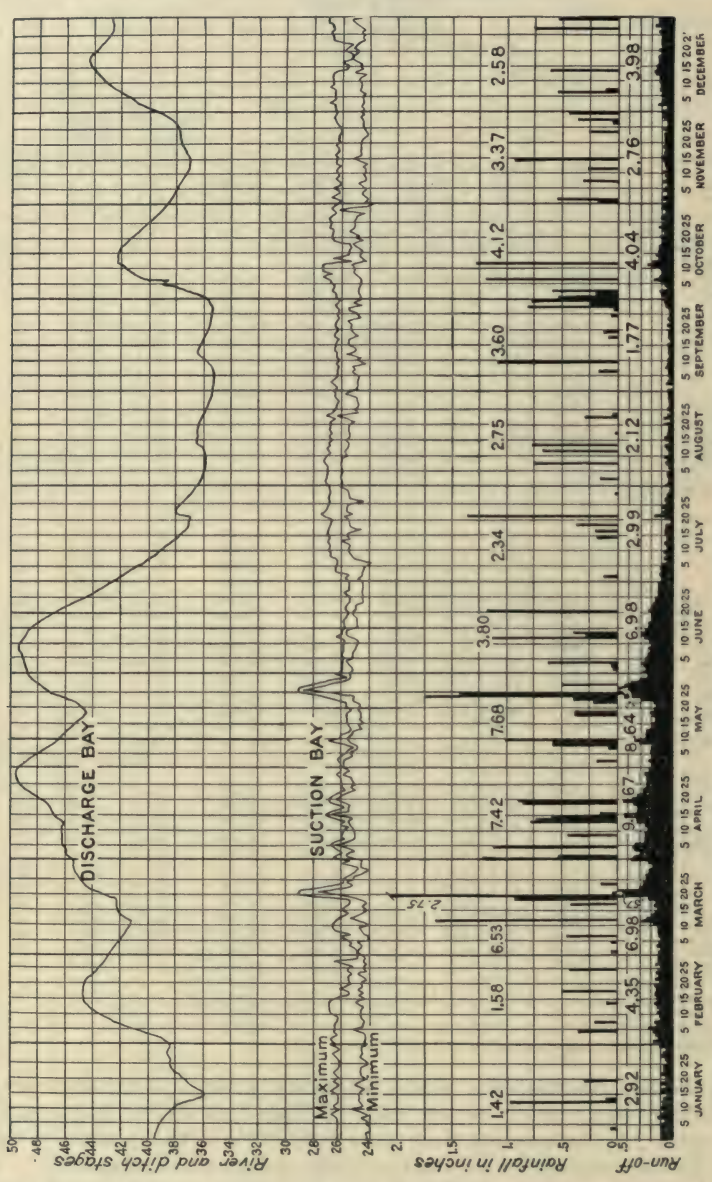


FIGURE 7.—Typical operating conditions of a plant having a high capacity. South Beardstown drainage and levee district, 1927

the Eldred. Although the designed capacity of the plant was only 0.382 inch in 24 hours at a total head of 25.5 to 27 feet, the run-off pumped occasionally exceeded one-half inch in 24 hours at lower heads. The data obtained from this district indicate that where seepage is

great the pumping plant should be designed for a run-off of about one-half inch in 24 hours.

The importance of operating the most efficient pumping units at proper speeds is indicated by the records for September and October, 1928. Pumping was done with units No. 1 and No. 3 at 310 revolutions per minute and No. 3 at 293 revolutions per minute. As a result of tests on October 11, the speed of unit No. 2 was reduced to 266 revolutions per minute beginning October 18. Although the average static lift was slightly greater for October than for September, the average power consumption dropped from 33.3 indicated horsepower-hours per acre-foot in September to 30.9 in October. The actual saving for the month, at 2.4 indicated horsepower-hours per acre-foot on the 1,814 acre-feet pumped, amounted to $32.50.

COST OF PUMPING

The monthly charges for power in 1925 were as follows: First 6,250 kilowatt-hours at 5.8 cents, next 6,250 kilowatt-hours at 4.5 cents, and additional kilowatt-hours at 3.6 cents. A quantity discount was allowed, computed as 1 per cent for each 900 kilowatt-hours but limited to 50 per cent when the monthly consumption exceeded 45,000 kilowatt-hours. A further discount of 10 per cent from the net bill was allowed when it was paid in 10 days. The minimum bill was $12 per horsepower of the motors in use driving the pumps.

From January 1, 1926 to June 15, 1928, the monthly charges were: First 6,250 kilowatt-hours at 5 cents, next 12,500 kilowatt-hours at 3.5 cents, and additional kilowatt-hours at 2.3 cents. Discounts and other contract conditions were the same under this rate as for the Banner Special plant (p. 17).

On June 16, 1928, the plant began operating on the optional off-peak rate (p. 21). The district had one 150-horsepower motor sealed off, making the connected load 400 horsepower and the net primary charge $300 monthly. This minimum charge continued through October, 1930. Then another 150-horsepower motor was sealed off, which reduced the demand charge to $187.50 net per month.

From June 16 to December 31, 1928, the plant consumed 300,700 kilowatt-hours, which cost $4,965. Under the optional rate in effect prior to June 16, 1928, it is estimated the cost would have been $996 greater. However, only 400 kilowatt-hours were billed on the day rate during 1928. The estimated saving by the district through pumping on the off-peak rate was $998 in 1929 and $1,241 during 1930. Even though the district increased the operator's salary $25 monthly for pumping at night, considerable saving was made by off-peak pumping at this plant.

The cost of power from 1919 to 1930, inclusive, is given in Table 26. The average power consumption during the six years 1925 to 1930 was 815,813 kilowatt-hours, or 19 per cent greater than the 12-year average. It may be seen that the cost per kilowatt-hour decreased considerably after 1921.

TABLE 26.—*Power used by South Beardstown drainage pumping plant, 1919 to 1930*

Year	Amount of power		Cost of power		
	Kilowatt-hours	Per cent of average	Total	Per kilowatt-hour	Per acre assessed
			Dollars	*Cents*	*Dollars*
1919	463,400	69	10,408.00	2.22	1.42
1920	590,600	86	16,107.07	2.73	2.19
1921	452,700	66	15,180.55	3.35	2.06
1922	714,300	104	16,619.14	2.33	2.26
1923	458,000	67	9,866.80	2.15	1.34
1924	637,400	93	11,805.18	1.85	1.61
1925	516,076	75	10,665.01	2.07	1.45
1926	1,170,600	171	18,964.33	1.62	2.58
1927	1,255,100	183	19,796.53	1.58	2.69
1928	636,600	93	11,126.12	1.75	1.51
1929	867,900	127	13,975.00	1.61	1.90
1930	448,600	66	8,249.00	1.84	1.12
Average	684,729		13,563.56	1.98	1.84

The operating costs are given in Table 27. The supplies and repairs for 1927 include an item of $831 for repairing a motor which burned out in 1926 after standing idle for about four years. The overhead expenses were particularly large during 1926 and 1927, on account of the necessity of spreading a special assessment and selling bonds to meet the heavy maintenance expenses during these flood years.

TABLE 27.—*Operating costs, including fixed charges, for South Beardstown drainage pumping plant, 1925–1930*

Year	Fixed charges	Electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 dollars	6,102	10,665	1,241	827	70	270	363	19,538
1926 do	6,102	18,964	1,808	522	130	203	1,369	29,128
1927 do	6,102	19,797	1,823	1,367	128	187	2,148	31,552
1928 do	6,102	11,126	1,490	253	68	152	694	19,885
1929 do	6,102	13,975	1,822	389	106	221	449	23,064
1930 do	6,102	8,249	1,550	189	64	162	287	16,603
Average do	6,102	13,796	1,622	596	95	199	885	23,295
Per cent of total	26.2	59.2	7.0	2.6	0.4	0.8	3.8	100

BAY ISLAND DRAINAGE AND LEVEE DISTRICT

The Bay Island drainage and levee district stretches approximately 10 miles along the east side of the Mississippi River. Eliza Creek now drains about 26,000 acres into the district, but recently construction has been begun on a channel to divert the stream. The pumping plant has the largest capacity of any on which records were kept, and likewise drains the largest area. The land in this district is high in relation to the river, and as a result the pumping lifts are generally low.

Subdistrict No. 1 of Union drainage district lies between the north line of the Bay Island district and the Copperas Creek diversion levee, and its run-off is pumped by the Bay Island plant. The assessed area of this subdistrict is 4,257 acres, and that of the Bay Island district is 19,334 acres, making the total of 23,591 acres given in Table 2. The average costs per assessed acre have been computed on the basis of the total acreage, although the Union district has an agreement to pay only one-sixth the annual operating costs.

This plant has received such excellent care that although it began operating in 1909 the equipment was in good repair at the end of 1929.

FIGURE 8.—Exterior view of Bay Island drainage pumping plant showing arrangement of suction and discharge pipes

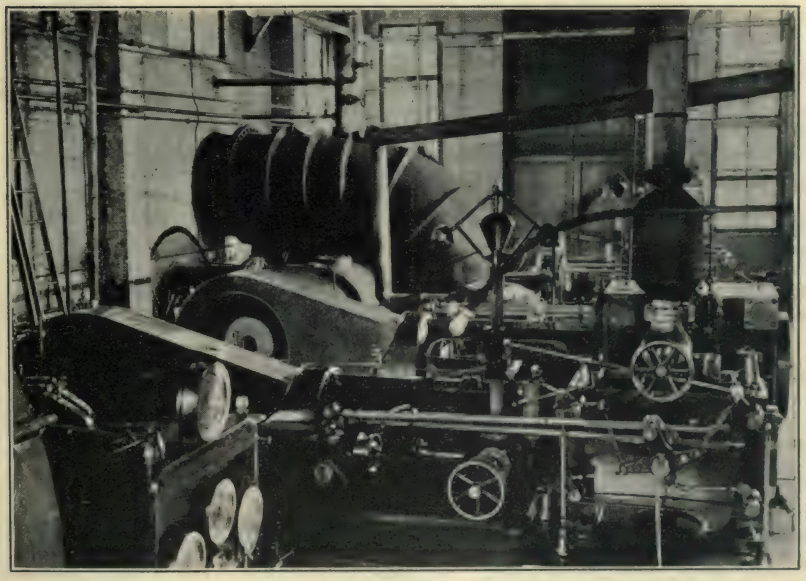


FIGURE 9.—Interior view of Bay Island drainage pumping plant showing 500-horsepower cross-compound Corliss engine direct-connected to 60-inch pump

An exterior view of this plant is shown in Figure 8, and an interior view in Figure 9. The two pumping units are described in Table 1.

The speed of each pump is usually varied from 100 to 124 revolutions per minute, although a slightly greater variation is possible by adjusting the governors on the engines. Steam is supplied by two water-tube boilers, each rated at 552 horsepower. An automatic stoker is fed by gravity from a 40-ton elevated hopper. Draft fans for the boilers are driven by small steam engines. The trash screen originally provided across the suction bay was removed some time previous to 1925, on account of trouble with accumulations of ice and débris.

OPERATION OF PLANT

The operation records are summarized in Table 28. The run-off during the 6-year period was unusually great. During the period 1911 to 1918 the average operation of the plant was equivalent to 2,300 hours per year for one unit, while during 1925 to 1930 it was equivalent to 4,282 hours of single-unit operation per year. The engines developed during the earlier period an average of 970,000 indicated horsepower-hours per year, and during the later period 1,934,453. In July, 1929, and June, 1930, unusually heavy local rains necessitated the pumping of a large amount of water. These rains were less severe on the other districts. The rains that caused the heavy pumping in September and October, 1926, were more widespread.

TABLE 28.—*Monthly operations of Bay Island drainage pumping plant, 1925–1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower hours operated	Coal used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				*Indicated horsepower hours*	*Brake horsepower hours* [1]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
January	0.60	0.27	1,161	0.56	26,380	75,400	19.7	17.3	4	76
February	1.95	2.17	9,382	3.23	211,730	605,190	20.0	17.6	22	78
March	1.35	1.53	6,617	3.31	54,860	442,630	20.3	17.9	22	76
April	3.46	.92	3,982	3.79	94,470	270,030	19.6	17.3	26	73
May	.89	.60	2,587	3.21	62,960	179,960	19.3	17.0	23	70
June	5.78	1.39	6,006	5.42	152,250	435,190	19.3	17.0	39	67
July	3.26	.99	4,290	4.69	104,170	297,750	21.1	18.5	31	76
August	2.30	.29	1,252	3.09	31,600	88,610	21.5	18.9	20	76
September	5.75	.42	1,837	1.64	40,000	114,340	18.9	16.6	12	76
October	2.32	.86	3,736	2.22	85,630	244,750	19.9	17.5	15	76
November	1.50	.83	3,575	2.18	80,250	229,390	19.5	17.1	15	76
December	1.81	.55	2,375	1.21	49,750	142,200	18.2	16.0	9	76
Total or average	30.97	10.82	46,800	3.31	1,093,450	3,125,440	19.8	17.4	23	75
1926										
January	1.46	.83	3,614	3.72	88,250	225,220	20.0	17.6	26	72
February	1.48	1.00	4,327	2.97	100,250	274,060	20.3	17.9	20	77
March	2.02	.93	4,027	4.42	100,250	274,120	21.9	19.2	28	77
April	1.55	1.54	6,673	7.86	180,750	542,320	26.1	23.0	41	85
May	1.40	.91	3,945	5.80	97,000	256,210	20.8	18.3	38	75
June	6.66	2.11	9,159	4.02	214,000	599,460	20.8	18.3	26	78
July	3.80	.77	3,329	1.68	75,250	203,000	19.4	17.1	12	76
August	12.30	1.44	6,222	1.84	135,250	383,150	19.6	17.2	13	79
September	9.05	5.77	24,999	5.87	604,250	1,809,770	23.0	20.3	35	84
October	2.24	4.38	18,964	7.65	481,000	1,607,390	24.7	21.7	43	86
November	4.00	2.14	9,259	4.65	214,500	578,800	15.9	14.0	40	60
December	1.70	1.34	5,816	4.94	139,500	479,700	20.9	18.4	32	77
Total or average	47.66	23.16	100,334	5.36	2,430,250	7,233,200	21.9	19.2	34	79

[1] Engine efficiencies assumed as 88 per cent.

TABLE 28.—*Monthly operations of Bay Island drainage pumping plant, 1925–1930*—Continued

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower hours operated	Coal used	Power used per acre-foot: Indicated horsepower hours	Power used per acre-foot: Brake horsepower hours	Overall efficiency	Average load on engine
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
January	.77	.83	3,606	5.66	95,500	231,730	18.5	16.3	42	62
February	2.40	2.80	12,148	5.35	316,000	772,890	18.3	16.1	40	62
March	5.25	2.72	11,796	7.99	341,000	934,820	22.9	20.1	48	70
April	4.50	4.28	18,542	10.24	504,000	1,790,590	27.9	24.5	50	90
May	6.40	3.73	16,153	9.41	471,500	1,468,810	26.2	23.1	49	79
June	5.95	3.59	15,542	9.55	436,500	1,472,970	27.3	24.1	48	86
July	2.10	.94	4,069	6.73	108,500	304,960	21.6	19.0	43	71
August	2.25	.38	1,632	6.44	44,000	118,240	20.9	18.4	42	68
September	3.25	.34	1,452	5.91	38,500	99,450	19.8	17.4	41	66
October	6.20	1.61	6,984	7.86	187,000	586,000	24.2	21.3	45	80
November	2.45	.97	4,219	6.00	106,000	309,990	21.2	18.6	39	74
December	2.59	.92	4,008	6.57	107,630	293,450	21.1	18.6	43	69
Total or average	44.11	23.11	100,151	8.22	2,756,130	8,383,900	24.1	21.2	47	77
1928										
January	.37	.70	3,030	5.20	75,000	205,400	20.8	18.3	34	74
February	2.52	1.94	8,400	7.51	231,800	652,000	23.9	21.0	43	76
March	2.20	1.45	6,290	8.49	182,000	522,300	25.5	22.5	46	78
April	3.56	2.27	9,850	11.71	339,100	1,070,800	33.4	29.4	48	85
May	2.68	1.28	5,560	9.85	175,700	490,500	27.1	23.9	50	76
June	7.59	.92	3,970	6.18	104,400	284,300	22.0	19.4	38	74
July	4.03	1.92	8,330	7.11	219,200	653,300	24.1	21.2	40	81
August	4.89	1.51	6,540	7.36	176,500	515,500	24.2	21.3	42	79
September	1.97	.82	3,570	8.90	107,700	304,800	26.2	23.1	46	76
October	3.87	1.30	5,630	8.49	161,800	462,200	25.2	22.2	46	77
November	4.46	2.71	11,740	9.66	352,400	1,092,500	28.6	25.2	46	84
December	1.67	1.51	6,550	7.24	176,900	511,200	24.0	21.1	41	78
Total or average	39.81	18.33	79,460	8.49	2,302,500	6,764,800	26.2	23.0	44	80
1929										
January	3.23	.90	3,889	7.81	107,440	282,000	24.5	21.6	44	78
February	.99	.92	3,997	5.96	107,400	280,000	23.7	20.9	34	78
March	1.82	4.35	18,842	12.09	635,840	1,975,000	35.4	31.2	47	92
April	7.68	4.38	18,987	12.88	649,000	2,013,000	35.8	31.5	49	92
May	1.83	3.83	16,618	10.44	509,000	1,403,000	28.6	25.1	50	82
June	6.24	1.22	5,275	7.32	145,040	390,000	25.0	22.0	40	80
July	9.21	3.72	16,110	5.94	419,620	1,131,000	23.7	20.9	34	80
August	2.00	.77	3,326	5.51	89,090	236,000	23.9	21.1	32	79
September	3.73	.42	1,822	5.18	47,300	120,000	22.3	19.6	32	76
October	4.12	.67	2,895	4.42	74,710	189,000	22.1	19.4	28	75
November	1.78	.97	4,207	4.81	112,540	282,000	22.7	19.9	29	75
December	.87	.55	2,368	5.14	64,200	161,000	22.9	20.2	31	74
Total or average	43.50	22.70	98,336	9.22	2,961,180	8,462,000	29.1	25.6	44	85
1930										
January	2.29	.35	1,532	3.64	40,380	103,200	22.0	19.4	23	73
February	1.27	2.05	8,868	6.31	241,790	639,900	23.6	20.7	37	76
March	1.34	1.59	6,889	6.98	193,630	518,400	24.6	21.6	39	77
April	2.32	.76	3,314	5.92	93,300	212,600	21.0	18.4	39	65
May	3.50	.54	2,329	6.36	66,160	167,700	23.5	20.7	37	73
June	9.17	3.62	15,668	5.93	418,380	1,115,800	23.3	20.5	35	77
July	1.40	1.44	6,229	7.00	156,040	462,800	24.3	21.4	40	85
August	1.02	.19	804	4.83	22,210	55,900	22.7	20.0	29	72
September	.54	.09	405	4.14	10,830	27,300	22.0	19.3	26	72
October	2.16	.14	591	3.94	16,000	40,400	22.3	19.6	24	72
November	1.62	.18	764	4.50	20,410	51,800	22.1	19.5	28	73
December	.99	.21	896	4.81	23,250	55,400	20.2	17.8	33	68
Total or average	27.62	11.16	48,289	6.14	1,302,380	3,451,200	23.3	20.5	36	76

The plant was more economical of coal than any other steam plant studied. Its average consumption per indicated horsepower-hour was 3.2 pounds, whereas that of the next best steam plant was 5 pounds. The stoker, furnace, boiler, steam piping, and engine were of good design for this type of plant. The district has always employed

competent operators, but the increased labor expense seems amply justified by the care given to the plant. The power consumption per acre-foot of water pumped indicates that the pumps and piping of this plant were comparatively efficient, although the impellers were badly worn and chipped by numerous logs which trash screens would have kept out of the pumps and considerable trouble was experienced in getting the discharge pipes to run full, probably because of air leaks.

The plant did not have sufficient capacity to control the water level in the suction bay, which on numerous occasions rose above 33 feet on the gage—the maximum allowable stage for proper drainage. When Eliza Creek has been diverted the capacity of the plant no doubt will be adequate, as the work planned will reduce the watershed area by almost one-half.

There was considerable variation in the stages of the suction bay, as is common with steam plants. Such plants are operated as infrequently as possible due to the time required and the stand-by losses incurred in firing up boilers, and when started they pump the water down as low as possible. This is a disadvantage of the steam plant, as both electric and oil-engine plants can be started readily and a fairly uniform water stage maintained in the suction bay. This usually gives better drainage to the lower lands and somewhat reduces the average static lift.

COST OF PUMPING

The operating costs are given in Table 29. The fixed charges are much lower than if the plant had been built at present prices. The average cost of coal during the 6-year period was $5.52 per ton delivered to the plant, and did not vary from this more than 25 cents in any year.

TABLE 29.—*Operating costs, including fixed charges, for Bay Island drainage pumping plant, 1925–1930*

Year	Fixed charges	Coal	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 dollars	7,881	9,090	5,237	1,966	400	732	1,897	27,203
1926 do	7,881	20,915	7,552	2,731	1,400	350	2,048	42,877
1927 do	7,881	22,842	9,004	5,145	1,639	139	2,339	48,989
1928 do	7,881	19,007	8,103	2,603	947	363	2,156	41,060
1929 do	7,881	22,776	8,159	2,944	1,808	110	2,283	45,961
1930 do	7,881	8,586	4,586	595	695	257	1,226	23,826
Average	7,881	17,203	7,107	2,664	1,148	325	1,991	38,319
Per cent of total	20.6	44.9	18.5	7.0	3.0	0.8	5.2	100

The cost of supplies and repairs were greater than those at any other plant, but are not believed to have been extraordinary considering the age and size of the plant. The overhauling of the furnaces and boilers was begun in 1926, and in 1927 the following payments were made: For stoker repair parts, $471; for boiler tubes, $898; for special labor on boilers, $337; for furnace brick, $150; for fire brick, $295. The 1928 repairs included new engine dash pots, $400; boiler tubes, $795; packing, $217; repair parts for coal elevator, $235. In 1929 an engine bearing cost $360, and other items were smaller in amount.

CRANE CREEK DRAINAGE AND LEVEE DISTRICT

The Crane Creek drainage and levee district, on the west side of the Illinois River, is approximately 4 miles long and 2¾ miles wide.

The pump house is a wooden structure on concrete foundations, with part of the floor of the building suspended over the suction bay. The pumping unit, described in Table 1, is operated usually between 150 and 175 revolutions per minute, but the speed varies greatly with slight changes in the steam pressure. A hand-fired return tubular boiler furnishes steam for the plant; draft for the boiler is obtained by a high metal smokestack.

OPERATION OF PLANT

Records kept by the operator indicate that during 1916 to 1921, the plant ran an average of 835 hours per year and consumed about 435 tons of coal annually. During the period 1925 to 1930 the plant ran an average of 1,729 hours and consumed an average of 835 tons of coal annually. The operation records for the latter period are given in Table 30.

TABLE 30.—*Monthly operations of Crane Creek drainage pumping plant, 1925 to 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Coal used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours* [1]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
February [2]	1.93	1.15	596	12.29	23,690	97,120	27.6	24.8	61	62
March	2.02	1.55	805	11.82	31,460	128,985	29.3	26.4	55	68
April	3.34	1.23	637	10.40	25,130	103,020	27.2	24.5	52	62
May	1.40	.60	310	7.96	12,190	49,980	23.6	21.2	46	54
June	2.91	.44	226	7.27	8,440	34,590	24.8	22.3	40	60
July	4.85	.44	228	7.07	8,200	33,620	24.4	22.0	40	61
August	5.70	.84	435	6.72	15,390	63,110	23.9	21.5	39	61
September	4.15	.28	146	6.68	5,150	21,100	24.3	21.9	38	62
October	3.96	.81	422	7.06	15,150	62,100	24.0	21.6	40	60
November	2.65	1.30	675	7.65	24,650	101,055	24.6	22.1	43	61
December	1.04	.81	418	7.76	14,980	61,420	23.6	21.3	45	59
Total or average	33.95	9.45	4,898	9.08	184,430	756,100	25.8	23.2	48	62
1926										
January	1.31	.88	457	7.53	16,690	57,000	23.5	21.0	44	57
February	2.28	1.35	702	8.80	26,150	84,800	22.8	20.3	53	54
March	3.08	1.36	706	11.58	29,500	107,190	28.7	25.5	56	61
April	3.79	3.56	1,846	12.96	72,770	291,500	31.6	28.1	56	71
May	2.52	1.24	644	11.82	26,010	98,570	28.8	25.6	56	63
June	5.79	1.83	950	10.12	37,710	131,580	27.2	24.2	51	61
July	3.67	.59	306	8.07	11,440	41,480	25.6	22.8	43	61
August	3.07	.64	334	8.12	12,480	46,220	26.1	23.2	43	62
September	12.17	5.96	3,093	13.67	130,400	330,260	31.4	28.0	60	66
October	3.96	5.48	2,843	15.98	122,170	330,100	34.2	30.4	64	71
November	4.60	3.97	2,063	13.50	82,840	286,700	32.3	28.8	57	72
December	1.77	2.80	1,454	15.67	64,970	236,600	35.8	31.9	60	71
Total or average	48.01	29.66	15,398	13.15	633,130	2,042,000	31.1	27.7	58	67
1927										
January	1.10	.98	507	9.25	21,710	52,900	23.5	20.9	54	49
February	1.61	2.19	1,138	14.11	57,020	152,310	30.2	26.8	64	54
March	5.98	5.41	2,808	11.63	117,460	361,730	29.0	25.8	55	62
April	6.78	7.26	3,767	14.64	171,650	553,580	33.1	29.5	61	65
May	8.14	5.34	2,772	15.05	134,040	425,880	34.6	30.8	60	64
June	3.47	4.77	2,475	17.81	118,500	441,710	40.2	35.8	61	75

[1] Engine efficiencies assumed as 89 to 90 per cent.
[2] Records commenced Feb. 10.

TABLE 30.—*Monthly operations of Crane Creek drainage pumping plant, 1925 to 1930*—Continued

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Coal used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours*		
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
July	3.14	1.50	780	10.20	29,790	94,130	27.2	24.2	52	63
August	2.75	.89	463	7.63	16,560	50,800	24.7	22.0	42	62
September	3.60	.51	264	6.81	9,440	27,810	23.8	21.1	39	59
October	4.12	1.42	735	12.03	30,650	93,670	28.7	25.6	58	61
November	3.37	.94	489	9.06	17,330	61,370	28.3	25.2	44	71
December	2.58	1.53	795	14.45	33,690	123,890	35.1	31.3	56	74
Total or average	46.64	32.74	16,993	13.68	757,840	2,439,780	32.4	28.8	58	65
1928										
January	.25	1.49	771	11.57	28,810	153,500	32.2	28.7	49	77
February	1.60	1.49	774	13.29	31,750	161,300	33.7	30.0	54	73
March	1.23	.97	505	10.55	19,120	94,800	30.4	27.0	48	71
April	3.42	1.38	714	11.48	28,060	138,100	31.3	27.8	50	71
May	2.52	.90	467	8.85	17,060	81,700	28.3	25.2	43	69
June	7.38	1.40	726	7.53	24,940	124,200	27.7	24.6	37	72
July	4.29	1.01	526	9.40	18,920	95,900	29.5	26.2	44	73
August	4.01	1.31	682	7.86	23,500	117,700	27.9	24.9	39	72
September	4.13	.59	309	6.94	11,290	48,600	25.4	22.7	37	62
October	3.57	.78	403	7.00	15,350	60,400	24.2	21.6	40	57
November	3.67	1.79	927	7.22	33,940	148,100	25.8	23.0	38	63
December	1.79	1.49	776	9.20	31,400	129,200	26.9	24.0	47	59
Total or average	37.86	14.60	7,580	9.42	284,140	1,353,500	28.9	25.7	45	69
1929										
January	4.38	2.19	1,136	10.38	42,230	183,400	30.6	27.3	46	73
February	.42	1.50	778	10.95	28,980	129,800	31.7	28.2	48	76
March	3.84	4.21	2,185	14.37	86,840	416,400	36.2	32.2	54	81
April	4.89	3.75	1,945	17.89	85,310	419,900	41.0	36.5	60	83
May	4.88	3.43	1,779	16.72	76,540	367,000	39.2	34.8	59	81
June	4.17	1.80	932	14.69	38,480	176,900	36.0	32.1	56	78
July	7.31	3.51	1,821	14.16	72,320	340,700	35.5	31.6	55	80
August	1.93	.78	403	9.61	15,830	59,900	28.2	25.1	47	64
September	3.12	.53	275	6.75	9,690	37,500	25.9	23.0	36	65
October	3.57	.58	302	7.43	10,380	43,500	27.4	24.4	37	71
November	3.67	.68	353	8.30	12,500	52,600	28.3	25.2	40	71
December	.89	.95	495	8.65	17,440	74,800	28.7	25.5	41	72
Total or average	43.07	23.91	12,404	13.78	496,540	2,302,400	35.2	31.4	54	78
1930										
January	3.05	1.09	565	10.41	20,630	104,900	30.9	27.5	46	75
February	1.95	2.63	1,367	11.62	52,080	264,900	32.2	28.7	49	75
March	2.02	1.80	932	13.79	38,710	191,500	34.2	30.4	55	73
April	1.36	1.11	577	11.77	22,580	110,500	31.9	28.4	51	72
May	1.64	.89	464	11.89	18,500	88,700	31.8	28.3	51	71
June	2.10	.51	263	6.57	8,900	41,900	26.5	23.5	34	70
July	2.60	.32	166	6.01	5,500	26,400	26.4	23.6	31	71
August	2.25	.20	104	6.22	3,500	16,300	26.1	23.2	33	69
September	2.25	.12	63	5.84	2,060	9,900	26.2	23.3	31	71
October	2.00	.29	149	5.69	4,880	23,200	25.8	23.0	30	70
November	1.75	.37	194	5.74	6,350	30,500	26.1	23.2	30	71
December	.35	.35	182	5.43	5,880	28,300	25.9	23.0	29	71
Total or average	23.32	9.68	5,026	10.67	189,570	937,000	31.0	27.6	47	73

The average coal consumption per indicated horsepower-hour ranged from 4.3 pounds in 1926 to 6.2 pounds in 1928, and averaged 5 pounds for the six years from 1925 to 1930. The steam end of this plant has not been as economical as that of the Bay Island plant. However, the Crane Creek plant was hand fired, burned a cheaper grade of coal, had a less efficient type of engine, was of cheaper construction, and was in a much poorer state of repair.

The daily records for 1926 are shown in Figure 10. These are typical of many steam plants, particularly as they show considerable fluctuation in the stage of the suction bay. The pumping plant was unable to hold the water in the suction bay below a 31-foot stage, especially in the fall of 1926 and the spring of 1927, and considerable damage resulted on the lower lands. There were numerous other occasions when the water in the suction bay rose rapidly because the plant did not have greater capacity. Even under ordinary conditions the variation between maximum and minimum stages of the suction bay usually was from 4 to 5 feet. This was due to the small amount of storage in the ditches and to the long intervals between pumping.

COST OF PUMPING

The operating costs of the district are given in Table 31. The fixed charges are low, because the plant was built at a time of comparatively low prices. The cost of coal averaged $5.27 per ton delivered to the plant. The items for supplies and repairs include $1,078 for replacing a smokestack in 1926, $509 for boiler tubes in 1927, and $248 for pump repairs in 1929. The administrative costs of this district were very low as compared with those of other districts. The average annual cost was quite low, but the capacity of the plant was insufficient to drain the land properly every year.

TABLE 31.—*Operating costs, including fixed charges, for Crane Creek drainage pumping plant, 1925–1930*

Year	Fixed charges	Coal	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 dollars	1,813	2,005	1,548	76	100	14	81	[1] 5,637
1926 do	2,037	5,559	2,276	1,281	250	19	248	11,670
1927 do	2,037	6,990	2,317	808	264	16	580	13,012
1928 do	2,037	3,162	1,823	257	118	133	591	8,121
1929 do	2,037	5,888	2,087	786	288	312	138	11,536
1930 do	2,037	2,327	1,750	408	44	99	109	6,774
Average for 5.89 years do	2,037	4,402	2,003	614	181	101	297	9,635
Per cent of total	21.1	45.7	20.8	6.4	1.9	1	3.1	100

[1] For the period Feb. 10 to Dec. 31, 1925.

Although the Crane Creek plant was expensive to operate, the saving in operating expenses that could have been made with a new Diesel or electric plant probably would have been less than the additional fixed charges with such equipment.

HENDERSON COUNTY DRAINAGE AND LEVEE DISTRICTS NOS. 1 AND 2

The Henderson County drainage and levee districts Nos. 1 and 2, on the east side of the Mississippi River, form an area about 9 miles long and 2¾ miles wide. They are protected by the same river levee and are separated only by a railroad embankment. Drainage water from district No. 1 flows into district No. 2 through a culvert. The assessed area of 15,005 acres comprises 7,682 acres in district No. 1 and 7,323 acres in district No. 2. A sandy soil and a continual high river stage due to the backwater from the Keokuk Dam cause a

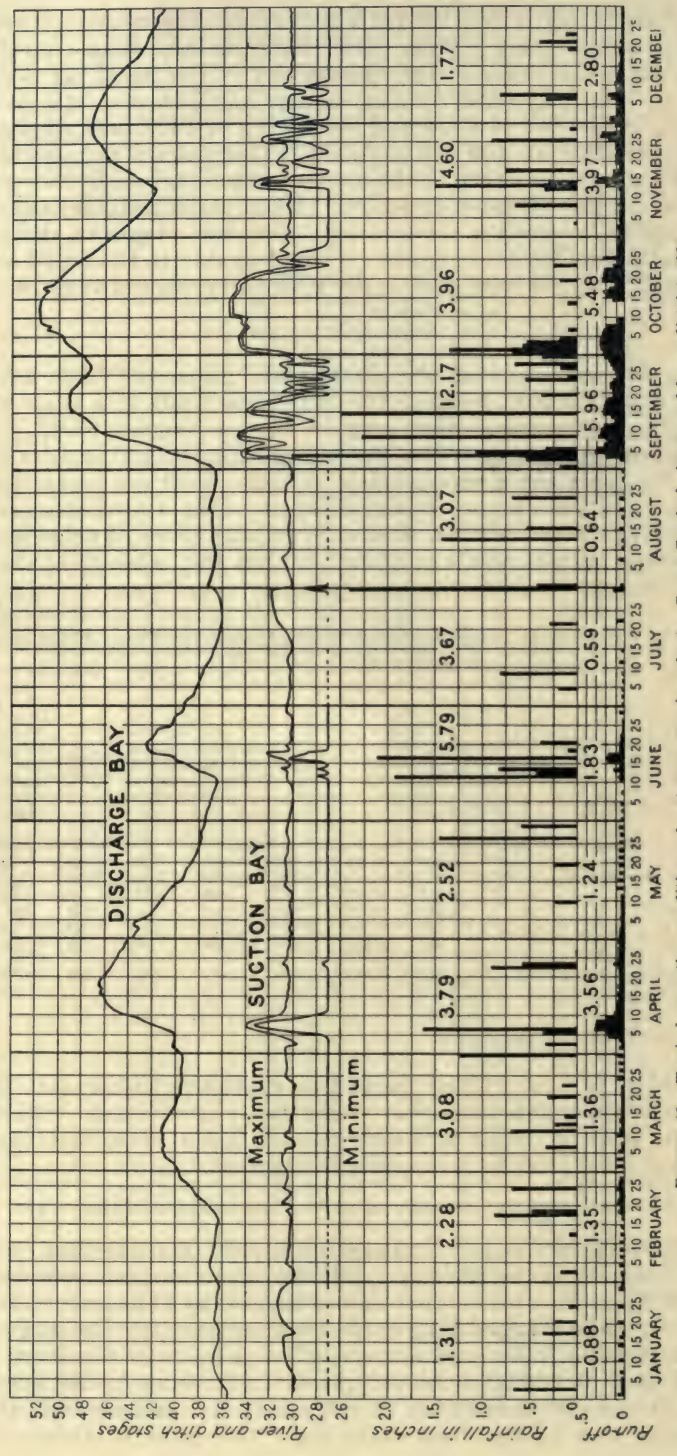


FIGURE 10.—Typical operating conditions of a steam pumping plant. Crane Creek drainage and levee district, 1926

large amount of seepage into the districts. A single pumping plant drains both districts, and the districts contribute equally to its support.

The plant is housed in a substantial brick building on concrete foundations. The steam engines were operated until May 13, 1928, when electric motors were substituted to drive the pumps. This change was made because the steam plant was in extremely poor mechanical condition and not dependable and was very costly to operate. The old pump casings were used, but new impellers were installed to increase the capacity of the pumps.

The two steam units, described in Table 1, were operated at speeds of 100 to 125 revolutions per minute, except when one engine ran both pumps, the speed then dropping to 95 revolutions per minute. The steam was supplied by two water-tube boilers, each rated at 257 horsepower. They were fired by two automatic chain stokers; draft was obtained with fans. An endless-chain conveyor carried the coal from the railroad siding into the building and up to a 70-ton hopper above the furnace.

These two electric units are also described in Table 1. Pump No. 1 is driven by a 350-horsepower induction motor through a 3.6 to 1 reduction gear. Secondary resistance control provides nine speeds for the pump from 124 to 244 revolutions per minute. Pump No. 2 is connected by a reduction gear to a shaft on which two 350-horsepower synchronous motors are mounted. The motors run at 900 and 720 revolutions per minute and the pump at 254 and 202 revolutions per minute.

The priming equipment is controlled by an automatic pressure switch so that when the vacuum drops the priming unit operates until the discharge pipe is filled with water. Considerable air gets into the drainage pumps, and the priming pump operates about one-fifth of the time the plant is in operation. On one occasion a slug of water was drawn into the vacuum pump and broke the cylinder head.

OPERATION OF PLANT

Operation records were kept at the plant from 1926 to 1930 and are given in Table 32. The steam plant was neither dependable nor economical during several years previous to the time it was abandoned. The consumption of coal was very high, averaging 6.2 pounds per indicated horsepower-hour, whereas for the Bay Island plant it was 3.2 pounds, and for the hand-fired Crane Creek plant 5 pounds per indicated horsepower-hour. The mechanical condition of the steam plant also was very poor. Figure 11 shows the operating record for 1928.

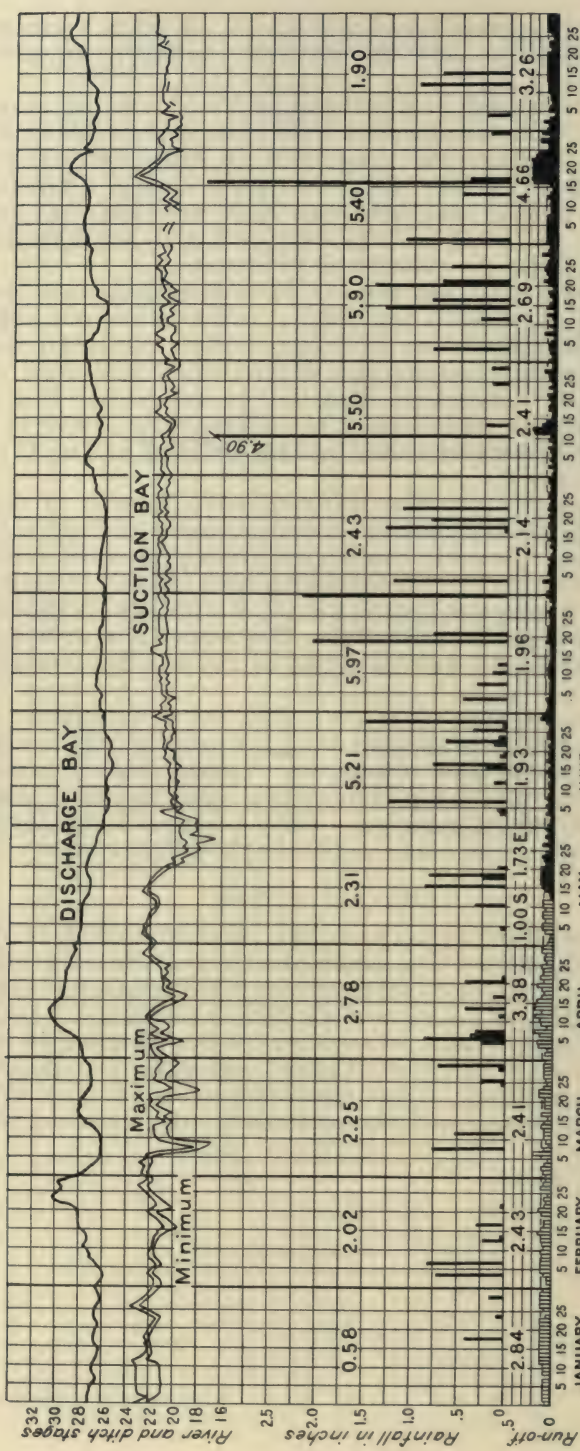


FIGURE 11.—Typical operating conditions of a plant pumping at comparatively low lift but with heavy and continuous seepage. Henderson County drainage and levee district, 1928

TABLE 32.—*Monthly operations of Henderson County drainage pumping plant, 1926 to 1930*

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Coal used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours [1]	Overall efficiency	Average load on engines
1926	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
March [2]	2.06	2.46	4,588	5.04	74,870	332,500	13.0	11.5	53	70
April	1.92	2.55	4,767	7.03	163,200	515,400	19.4	17.1	50	50
May	2.79	1.80	3,356	6.77	122,100	375,900	20.1	17.7	46	49
June	6.35	3.80	7,092	4.98	251,980	538,400	13.6	12.0	50	34
July	2.85	1.78	3,315	5.29	110,550	291,100	15.8	13.9	46	42
August	3.69	1.71	3,199	5.10	103,050	274,300	15.4	13.6	45	42
September	14.31	6.94	12,949	4.41	408,950	1,012,600	14.1	12.4	43	39
October	2.45	4.60	8,588	6.77	312,450	870,100	18.2	16.0	51	44
November	2.87	3.24	6,047	5.72	206,700	492,200	14.6	12.9	54	38
December	1.21	2.68	4,997	4.99	141,530	425,100	15.3	13.5	45	48
Total or average	40.50	31.56	58,898	5.49	1,895,380	5,127,600	15.6	13.8	48	43
1927										
January	.90	2.18	4,075	4.13	68,550	364,150	13.5	11.8	42	70
February	2.19	3.62	6,758	4.89	202,650	726,340	16.2	14.2	42	48
March	3.24	3.95	7,377	6.45	257,930	876,610	17.9	15.7	50	45
April	5.31	4.85	9,054	10.25	413,100	1,390,240	23.1	20.4	61	45
May	5.34	2.84	5,304	9.06	206,800	714,050	20.3	17.8	61	46
June	4.37	4.33	8,074	5.54	254,400	898,480	16.8	14.7	45	47
July	2.38	2.03	3,780	6.25	127,050	436,430	17.4	15.3	49	46
August	1.40	1.59	2,976	5.01	104,050	317,700	16.1	14.1	43	40
September	2.32	1.30	2,418	6.79	86,450	279,360	17.4	15.3	54	43
October	6.02	3.90	7,282	5.20	267,590	762,930	15.8	13.9	45	38
November	3.12	2.33	4,344	4.20	148,000	444,460	15.4	13.6	37	40
December	2.36	2.02	3,776	3.75	131,100	373,550	14.9	13.1	34	38
Total or average	38.95	34.94	65,218	6.26	2,267,670	7,584,300	17.5	15.4	49	44
1928										
January	.58	2.84	5,296	4.58	182,700	545,700	15.4	13.6	41	39
February	2.02	2.43	4,538	6.31	172,300	495,400	16.3	14.4	53	38
March	2.25	2.41	4,502	6.05	178,610	479,500	15.9	14.0	52	35
April	2.78	3.38	6,313	8.14	251,510	766,600	18.2	16.0	62	40
May [3]	.36	1.00	1,873	5.93	66,820	201,200	16.1	14.1	51	40
Total or average	7.99	12.06	22,522	6.33	851,940	2,488,400	16.5	14.5	53	38
						Kilowatt-hours				
May	1.95	1.73	3,224	6.77	114,160	71,600	29.8	22.9	31	65
June	5.27	1.93	3,595	5.41	126,190	74,200	27.7	22.3	27	64
July	5.97	1.96	3,656	5.42	132,500	66,000	24.2	21.9	31	60
August	4.42	2.14	3,998	5.27	143,060	68,700	23.0	20.6	31	58
September	5.50	2.41	4,496	6.22	162,170	85,900	25.6	23.0	33	64
October	5.90	2.69	5,028	6.19	185,500	89,700	23.9	21.5	36	58
November	5.40	4.66	8,689	6.63	307,080	169,200	26.1	23.1	35	66
December	1.90	3.26	6,084	6.74	228,840	106,600	23.5	21.7	39	58
Total or average	36.31	20.78	38,770	6.19	1,399,500	731,900	25.3	22.2	34	62
1929										
January	4.10	2.96	5,531	9.82	223,520	110,200	26.7	24.6	50	61
February	1.00	2.72	5,079	8.52	195,120	97,700	25.8	23.2	45	60
March	4.72	6.29	11,747	10.35	458,130	254,200	29.0	25.2	49	65
April	6.45	7.84	14,635	8.28	502,540	296,000	27.1	24.1	42	70
May	2.66	6.86	12,810	7.27	438,060	252,000	26.4	24.3	38	71
June	5.72	3.71	6,921	8.42	269,770	127,500	24.7	22.2	47	57
July	6.27	3.03	5,652	6.29	209,850	106,500	25.3	23.0	34	62
August	2.96	1.78	3,327	4.76	120,230	62,100	25.0	23.0	26	64
September	3.88	1.37	2,560	4.28	91,640	42,400	22.2	20.4	26	57

[1] Steam engine efficiencies assumed as 88 per cent; electric motor efficiencies assumed as 77 to 93 per cent.
[2] Records commenced Mar. 1.
[3] Steam engine replaced by electric motor on May 14.

TABLE 32.—*Monthly operations of Henderson County drainage pumping plant, 1926 to 1930*—Continued

Year and month	Rain fall	Water pumped		Average static lift	Rated horse-power-hours operated	Current used	Power used per acre-foot		Over-all efficiency	Average load on engines
		Run-off depth	Quantity				*Indicated horse-power-hours*	*Brake horse-power-hours*		
1929	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Kilowatt-hours*			*Per cent*	*Per cent*
October	4.44	1.61	3,012	4.14	107,980	49,400	22.0	20.5	26	57
November	1.48	2.24	4,188	4.50	150,340	68,300	21.9	20.1	28	56
December	.37	1.68	3,137	3.00	110,390	48,600	20.8	19.3	20	55
Total or average	44.05	42.09	78,599	7.57	2,877,570	1,514,900	25.8	23.3	40	64
1930										
January	1.50	1.44	2,689	3.21	94,940	41,800	20.8	19.2	21	54
February	1.25	2.53	4,722	4.98	171,820	77,200	21.9	20.2	31	56
March	.97	2.57	4,804	7.22	182,900	89,400	25.0	23.1	40	61
April	2.87	1.88	3,514	5.41	127,210	58,100	22.2	20.5	33	56
May	2.09	1.73	3,232	5.58	118,920	53,100	22.0	20.3	35	55
June	6.55	2.55	4,756	6.88	171,770	87,500	24.7	22.8	38	63
July	.63	1.08	2,017	5.16	73,670	34,800	23.1	21.4	31	58
August	1.11	.37	688	3.07	24,230	11,700	22.8	21.1	18	60
September	3.12	.59	1,095	2.97	38,500	19,500	23.9	22.1	17	63
October	2.46	1.38	2,583	4.36	92,940	44,000	22.8	21.1	26	59
November	2.47	1.10	2,058	3.62	73,150	33,500	21.8	20.1	23	57
December	.61	1.42	2,645	3.63	94,020	42,900	21.8	20.1	23	56
Total or average	25.63	18.64	34,803	5.19	1,264,070	593,500	22.9	21.1	31	58

When the plant was electrified new impellers were installed and the pump speeds increased, which lowered the pump efficiencies considerably. This is evident from a comparison of the power consumptions and over-all efficiencies of the steam plant with those of the electric plant. (Table 32.) The synchronous motor unit No. 2 was considerably more efficient when operating at low speed than the variable-speed motor unit No. 1, largely due to power loss in the secondary resistance coils of unit No. 1.

The plant capacity was rather inadequate for providing effective drainage to the district. The run-off pumped during March to May, 1929, was one-half greater than the rainfall of 13.83 inches, indicating that seepage was very large at high river stages.

COST OF PUMPING

The operating costs for this plant are given in Table 33. The average cost of coal was $4.36 per ton. Repairs to the steam equipment were very expensive, mostly for the boilers and furnaces. One of the engine frames broke in 1927, and was braced temporarily. Much of the repair work in 1927 and 1928 was of an emergency nature, to keep the steam equipment operating until electrification could be completed. The costs are shown for the full year 1926, although the operation records were not begun until March 1.

TABLE 33.—*Operating costs, including fixed charges, for Henderson County drainage pumping plant*

STEAM UNITS, 1926–1928

Year	Fixed charges	Coal or electric power	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1926 ..... dollars	6,894	12,043	4,304	5,131	1,000	488	930	30,790
1927 ..... do	6,894	17,011	6,863	5,270	1,362	403	1,631	39,434
1928 ..... do	2,523	5,458	2,968	5,774	756	82	1,481	[1] 19,042
Average for 2.366 years ..... do	6,894	14,587	5,974	6,836	1,318	411	1,708	37,728
Per cent of total	18.3	38.7	15.8	18.1	3.5	1.1	4.5	100

ELECTRIC UNITS, 1928–1930

1928 ..... dollars	4,308	13,579	1,520	180	302	143	1,885	[2] 21,917
1929 ..... do	6,795	25,324	3,017	94	41	119	2,081	37,471
1930 ..... do	6,795	11,502	2,440	511	8	39	1,934	23,229
Average for 2.634 years ..... do	6,795	19,136	2,649	298	133	114	2,240	31,365
Per cent of total	21.7	61.0	8.4	1.0	0.4	0.4	7.1	100

[1] Operated until May 13, 1928. [2] Began operating May 14, 1928.

The fixed charges on the electrified plant were computed as follows: The value of the steam plant in 1928 was determined as $32,867, by deducting from its first cost the estimated amount that would have accumulated in a depreciation fund during the 15 years that the plant had been in operation. To this was added the cost of electrification, $39,050, making the total value of the electric plant $71,917 in 1928. The buildings and pumps were estimated to have a further life of 20 years.

Electric current was bought at the following rates: First 100,000 kilowatt-hours per annum at 2.5 cents, next 400,000 kilowatt-hours per annum at 1.9 cents, and additional kilowatt-hours per annum at 1.5 cents. No discounts were allowed, and bills were rendered monthly.

SCOTT COUNTY DRAINAGE AND LEVEE DISTRICT

The Scott County drainage and levee district, on the east side of the Illinois River, extends along the river for about 6 miles and averages about 3¼ miles in width.

The steam and semi-Diesel units are housed separately in two brick buildings on concrete foundations. The steam units, Nos. 1 and 2 described in Table 1, did all the pumping from 1913 to July, 1928. Semi-Diesel unit No. 3 (fig. 16) was installed in 1928 to reduce the operating expenses and increase the plant capacity, and since then has done nearly all the pumping while the steam units have served as stand-by equipment.

The pumps of the steam units are suspended over the suction bay. Unit No. 1 is usually operated between 130 and 170 revolutions per minute and unit No. 2 between 180 and 235 revolutions per minute. Steam for the engines is furnished by two water-tube boilers. One of the fire boxes is equipped with a hand-operated stoker, while the other is hand-fired.

The building and foundations containing the semi-Diesel unit were constructed for two units, but only one has been installed. (Fig. 16.) It is identical with those at the McGee Creek plant and usually is operated between 320 and 355 revolutions per minute.

OPERATION OF PLANT

Records were kept on this plant from June 10, 1925, through 1930. The monthly summary is given in Table 34. On April 6, 1926, a break in the diversion levee on Mauvaisterre Creek permitted a considerable area to be flooded, and both units were operated continuously from April 7 to April 20. The diversion levee broke again on September 8, 1926, and by September 10 the plant was flooded and pumping was discontinued. The levee was repaired and pumping began again on February 18, 1927. The pumps operated continuously until April 4, when once more the levee broke, and the district was flooded. The plant resumed operation August 12, 1927. During 1928 the stages of the river were moderate, and the steam units were not operated 24 hours in any day. Considerably more pumping was necessary during 1929 than in 1928, but little was necessary in 1930 because of the drought.

TABLE 34.—*Monthly operations of Scott County drainage pumping plant, 1925 to 1930*

STEAM UNITS

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Coal or fuel oil used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours* [1]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
June [2]	3.06	0.19	198	7.30	11,670	40,840	23.0	20.3	44	34
July	3.23	.27	286	6.69	16,080	56,240	22.2	19.5	41	35
August	4.90	.28	291	6.38	15,760	55,120	21.3	18.8	41	35
September	2.86	.23	244	5.66	12,670	44,310	20.5	18.0	38	35
October	5.50	.62	647	5.98	34,290	119,970	21.5	18.9	38	36
November	2.69	.96	998	7.05	53,720	187,940	22.4	19.7	43	37
December	0.89	.65	678	7.31	33,640	117,680	21.8	19.1	46	39
Total or average	23.13	3.20	3,342	6.72	177,830	622,100	21.9	19.3	42	36
1926										
January	1.33	.60	623	8.10	28,670	70,870	20.8	18.3	54	40
February	2.07	1.08	1,125	9.17	51,160	144,810	23.5	20.7	54	46
March	2.59	1.45	1,506	12.01	69,130	238,790	29.0	25.5	57	56
April	4.61	5.44	5,665	14.34	280,260	874,300	32.2	28.3	61	57
May	1.89	1.08	1,120	12.40	54,240	169,725	27.7	24.4	62	50
June	6.25	1.26	1,314	10.62	65,250	187,245	26.0	22.9	56	46
July	3.72	.61	637	9.24	29,150	91,570	26.3	23.1	48	50
August	6.22	.62	642	9.16	32,650	69,725	19.8	17.5	63	34
September	12.41	2.14	2,230	7.18	94,600	301,465	28.2	24.8	35	58
Total or average	41.09	14.28	14,862	11.46	705,110	2,148,500	28.4	25.0	55	53
1927										
February [3]	.96	1.76	1,837	8.72	80,220	329,900	24.9	21.9	48	50
March	6.78	8.77	9,133	8.04	416,640	1,713,400	25.6	22.5	43	49
April	2.45	.99	1,035	11.64	51,750	212,800	28.0	24.7	57	49
August [4]	1.05	2.03	2,112	4.76	88,950	365,800	24.1	21.3	27	50
September	2.96	.90	933	7.50	40,510	166,600	25.4	22.4	40	52
October	3.59	2.45	2,557	12.00	125,940	517,900	27.5	24.2	60	49

[1] Engine efficiencies assumed as 88 per cent for steam engines and 75 per cent for semi-Diesel unit.
[2] Records commenced June 10.
[3] Pumping resumed Feb. 18.
[4] Plant flooded Apr. 4; pumping resumed Aug. 12.

TABLE 34.—*Monthly operations of Scott County drainage pumping plant, 1925 to 1930*—Continued

STEAM UNITS—Continued

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Coal or fuel oil used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours	Overall efficiency	Average load on engine
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Pounds*			*Per cent*	*Per cent*
November	3.99	1.31	1,366	10.84	66,930	275,200	26.1	22.9	57	47
December	1.86	1.85	1,922	14.81	99,400	408,820	30.7	27.0	66	52
Total or average	23.64	20.06	20,895	9.21	970,340	3,990,420	26.2	23.1	48	50
1928										
January	0.44	1.71	1,783	13.55	89,580	390,400	29.9	26.3	62	52
February	1.67	1.99	2,071	13.86	99,440	468,100	30.9	27.2	62	57
March	.97	1.11	1,151	11.49	53,810	232,700	27.6	24.3	57	52
April	3.69	1.90	1,981	12.49	95,940	410,500	28.3	24.9	61	51
May	3.22	1.49	1,556	10.07	74,360	277,100	24.3	21.4	57	45
June	5.48	1.23	1,278	8.88	64,700	199,500	21.3	18.8	57	37
July	2.79	.72	755	11.44	41,040	126,500	22.9	20.1	69	37
August	2.75	.04	40	11.53	2,280	6,700	22.7	20.0	70	35
September	3.72	.06	65	8.65	3,170	10,600	22.3	19.7	53	40
October	3.71									
November	3.00									
December	1.49	.65	674	10.62	33,030	121,500	24.6	21.7	59	44
Total or average	32.93	10.90	11,354	11.86	557,350	2,243,600	27.0	23.7	60	48

SEMI-DIESEL UNIT

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Coal or fuel oil used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours	Overall efficiency	Average load on engine
1928						*Gallons*				
July [5]	2.08	0.24	245	10.76	8,900	600	48.9	36.7	30	101
August	2.75	.61	635	9.11	23,500	1,470	43.7	32.8	29	89
September	3.72	.56	578	7.83	20,440	1,340	43.6	32.7	25	92
October	3.71	.85	890	7.61	33,300	2,100	39.2	29.4	27	78
November	3.00	1.00	1,041	9.41	40,600	2,930	41.4	31.1	31	80
December	1.49	.57	595	11.86	22,600	2,260	49.2	36.9	33	97
Total or average	16.75	3.83	3,984	9.18	149,340	10,700	43.2	32.4	29	86
1929										
January	3.58	1.56	1,625	11.54	61,820	4,530	48.4	36.3	33	95
February	.38	.96	1,001	12.41	41,160	2,720	47.2	35.4	36	86
March	3.72	1.94	2,016	17.14	92,460	6,500	55.9	41.9	42	91
April	4.83	2.35	2,447	18.44	106,100	8,520	60.4	45.3	42	104
May	7.11	2.61	2,714	16.62	108,140	9,160	58.6	43.9	39	110
June	2.56	1.60	1,666	13.75	66,730	4,900	51.0	38.3	37	96
July	4.16	1.37	1,425	15.39	61,890	4,300	52.4	39.3	40	90
August	2.43	.67	699	10.16	27,370	1,720	42.8	32.1	33	82
September	2.62	.36	380	8.41	14,650	860	39.2	29.4	29	76
October	5.92	.60	625	8.22	24,040	1,400	39.0	29.3	29	76
November	1.75	.79	826	9.25	32,380	1,920	40.3	30.2	32	77
December	1.18	.08	86	8.98	3,380	200	39.8	29.9	31	76
Total or average	40.24	14.89	15,510	14.48	640,120	46,730	52.3	39.2	38	95

STEAM UNITS

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Coal or fuel oil used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours	Overall efficiency	Average load on engine
1929						*Pounds*				
March		1.20	1,254	16.07	66,010	214,000	33.8	29.7	65	56
April		.94	981	18.57	54,240	189,000	38.2	33.6	67	61
May		1.93	2,008	16.29	101,460	346,000	34.2	30.1	65	60
June		.20	205	14.14	9,470	33,000	31.9	28.1	61	61
December		.67	696	8.44	31,710	82,000	23.4	20.6	50	45
Total or average		4.94	5,144	15.52	262,890	864,000	33.3	29.3	64	57

[5] Pumping commenced July 22.

TABLE 34.—*Monthly operations of Scott County drainage pumping plant 1925 to 1930*—Continued

SEMI-DIESEL UNIT

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Coal or fuel oil used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours	Overall efficiency	Average load on engine
1930	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*	*Indicated horsepower-hours*	*Brake horsepower-hours*	*Per cent*	*Per cent*
January	3.68	1.10	1,145	11.59	44,400	3,300	46.4	34.8	34	90
February	1.99	1.74	1,817	14.00	73,270	5,160	50.2	37.6	38	93
March	.82	1.28	1,331	15.15	59,220	4,400	49.6	37.2	42	84
April	1.27	.74	771	12.95	30,720	2,190	48.5	36.4	37	91
May	1.61	.63	656	13.32	27,220	1,980	48.7	36.5	38	88
June	4.21	.47	486	8.87	18,270	1,150	41.8	31.3	29	83
July	.42	.32	332	8.18	12,870	890	38.2	28.6	29	74
August	1.79	.18	189	7.61	7,330	500	36.8	27.6	28	71
September	2.78	.16	168	7.62	6,430	490	37.3	28.0	28	73
October	1.68	.21	216	5.77	8,010	600	35.2	26.4	22	71
November	2.14	.21	216	5.40	7,960	600	34.8	26.1	21	71
December	.51	.26	270	6.11	10,050	750	35.6	26.7	24	72
Total or average	22.90	7.30	7,597	12.03	305,750	22,010	46.2	34.6	36	86

STEAM UNITS

1930						*Pounds*				
February		0.47	490	12.89	23,070	80,000	29.7	26.1	60	55
November		.03	28	5.61	1,240	4,240	27.5	24.3	28	55
Total or average		.50	518	12.50	24,310	84,240	29.6	26.0	58	55

The plant had sufficient capacity to prevent damage from high water in 1929, although there were several occasions of a few days each in the spring when the level in the suction bay was above the desired maximum stage.

The years 1928 to 1930 were the only ones for which the records were complete and pumping was not interrupted by floods. The run-off pumped in 1928 amounted to 14.73 inches, of which 3.83 inches was pumped by the semi-Diesel unit after it began operating in July. In 1929, the semi-Diesel unit pumped 75 per cent of the total run-off of 19.83 inches and in 1930 pumped 94 per cent of the total run-off, 7.8 inches. Most of the pumping done by the steam plant in 1929 was during the spring flood, and in December after the coal pile began to heat.

Figure 12 shows the operation records for 1929. These constitute a typical example of the operation of a plant in which the oil-engine unit is used for regular pumping and steam units are used for stand-by service during periods of heavy run-off. The semi-Diesel unit was operated nearly half the time in 1929, its plant factor being 46.3 per cent. Its plant factor was 22 per cent for the period of pumping during 1928 and 20 per cent for 1930. The average power consumption during 1929 and 1930 was 37.7 brake horsepower-hours per acre-foot at a lift of 13.68 feet, which is comparatively high. The belt loss was large. The average pump efficiency was low because it was operated at too high a speed during much of the spring of 1929, but probably this was justified because even at high speed water could be pumped more economically with the semi-Diesel unit than with the steam units.

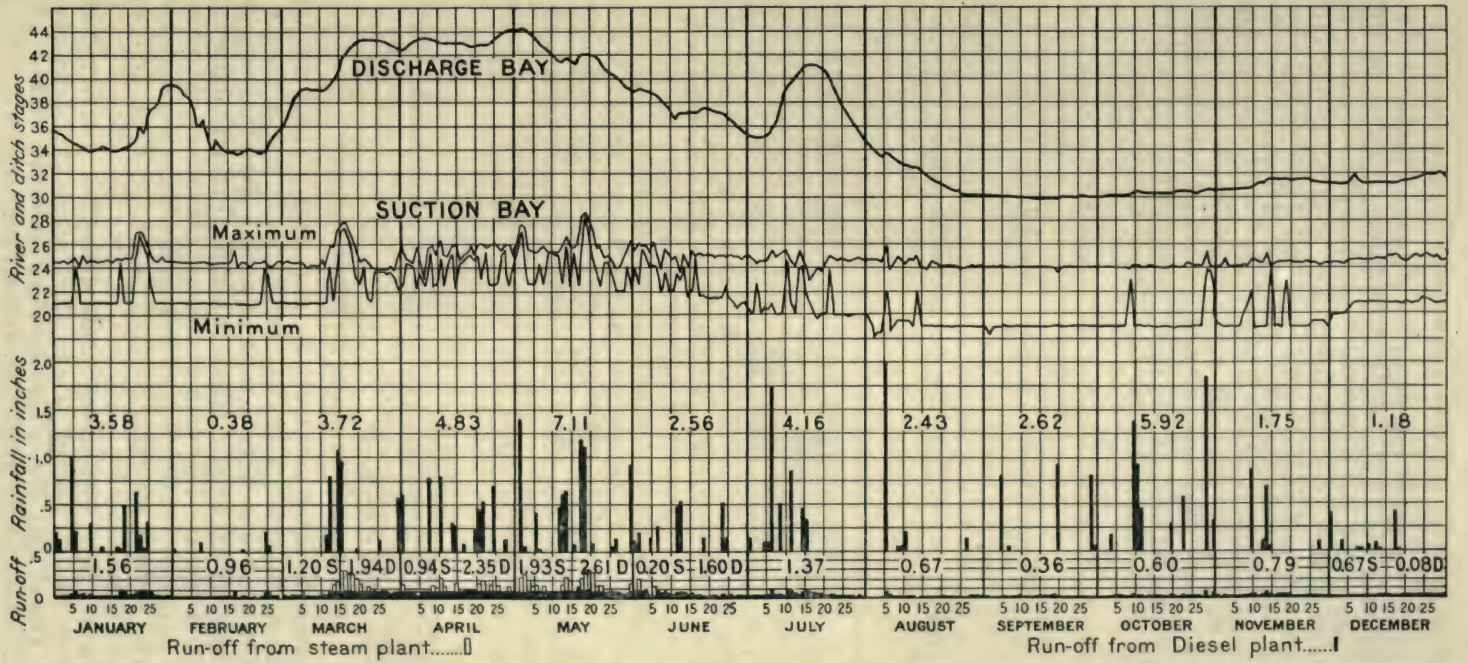


FIGURE 12.—Typical operating conditions of a plant where oil engines are used for regular pumping and steam units for stand-by service. Scott County drainage and levee district, 1929

COST OF PUMPING

The operating costs of this plant are shown in Table 35. Records were incomplete for 1925; floods interrupted pumping in 1926 and 1927; and the plant was converted from steam to oil engine in 1928. The average figures for steam operation, as given in the table, are based upon 1929 and 1930 records only and therefore represent only service as stand-by equipment. The cost of repairs for 1927 was large because of the flooding of the plant. Lumber and labor for repairs to the suction bay cost $731. The supplies and repairs for 1928 include $375 for a second-hand truck with which to haul coal. The cost of fuel oil used by the plant averaged 6.48 cents per gallon, which was greater than that for the McGee Creek plant.

TABLE 35.—*Operating costs, including fixed charges, for Scott County drainage pumping plant*

STEAM UNITS, JUNE 10, 1925, TO DECEMBER 31, 1930

Year	Fixed charges	Fuel oil or coal	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 dollars	2,471	1,650	1,235	300	150	157	146	[1] 6,109
1926 do	4,396	6,316	1,831	70	200	300	431	[2] 13,544
1927 do	4,396	9,745	3,655	1,851	466	250	1,273	[2] 21,636
1928 do	[3] 3,273	5,488	1,517	1,331	132	195	628	12,564
1929 do	1,872	2,160	683	453	181	40	134	5,523
1930 do	1,872	211	43	80	16	79	70	2,371
Average for 1929 and 1930 dollars	1,872	1,185	363	267	98	60	102	3,947
Per cent of total	47.4	30.0	9.2	6.8	2.5	1.5	2.6	100

SEMI-DIESEL UNIT, JULY 22, 1928, TO DECEMBER 31, 1930

1928 dollars	1,324	737	1,084	272	243	139	200	[4] 3,999
1929 do	2,975	2,983	1,781	312	450	172	216	8,889
1930 do	2,975	1,318	2,160	260	210	238	217	7,378
Average for 1929 and 1930 dollars	2,975	2,151	1,971	286	330	205	216	8,134
Per cent of total	36.6	26.4	24.2	3.5	4.1	2.5	2.7	100

[1] For period June 10, 1925, to Dec. 31, 1925.
[2] Plant flooded Sept. 10, 1926; pumping resumed Feb. 18, 1927; plant flooded again Apr. 4, 1927; pumping resumed Aug. 12. Costs for 1926 and 1927 omitted from averages.
[3] Based on stand-by operation after July 22, 1928.
[4] For period July 22, 1928, to Dec. 31, 1928.

ELDRED DRAINAGE AND LEVEE DISTRICT

The Eldred drainage and levee district extends along the east side of the Illinois River for 8½ miles, and varies in width from 1 to 2½ miles. The land is so high in relation to the river that considerable gravity drainage has been obtained through a concrete sluiceway near the pumping plant. The dam at Kampsville raises the river level along the upper end of the district and no doubt increases the seepage there. The district pumping plant is below the dam, and the lifts are not affected.

The original plant comprising steam units Nos. 2 and 3 (Table 1), began operating in August, 1911. To reduce the large operating expenses, Diesel unit No. 1 was installed in 1921. The engine was rated at 250 horsepower at 250 revolutions per minute and 200 horse-

power at 200 revolutions per minute, varying in proportion to the speed. Steam engine No. 3 was replaced with a 120-horsepower Diesel engine in 1929. The steam units were housed in a substantial brick building, and Diesel unit No. 1 in a hollow-tile building adjoining. Diesel engine No. 3 is housed in a small brick addition to the original building and belt connected to the pump.

The speed of unit No. 1 usually was between 205 and 215 revolutions per minute. Unit No. 2 usually was operated between 180 and 188 revolutions per minute after it was repaired in 1928, but previously was run as low as 155 revolutions per minute. Unit No. 3 was operated between 200 and 225 revolutions per minute when driven by the steam engine and between 200 and 215 revolutions per minute after being connected to the Diesel engine.

OPERATION OF PLANT

Since Diesel unit No. 1 was installed in 1921 it has been used to pump as much of the run-off as possible. In addition to the run-off pumped from the district, considerable gravity drainage was obtained from 1925 to 1927 and in 1930. Since it was desirable to hold the stage of the suction bay below 22 feet during 1928 and 1929 on account of the rice crops, it was necessary to pump all the run-off during those years except some in September and October, 1929.

The operation records are given in Table 36. The run-off during 1925 and to September, 1926, was so small that unit No. 1 handled it all except in April, 1926. Heavy pumping continued throughout the floods of 1926 and 1927, but the plant could not prevent flooding of much low land because the steam units were in poor condition and unable to pump their rated capacity. Unit No. 2 was overhauled during the winter of 1927 and 1928, and thereafter the plant could control the water level in the suction bay except for a few days in March and May, 1929. No pumping was necessary after July, 1930, as gravity drainage was adequate. It was not necessary to operate the steam units after June, 1929, or during 1930.

TABLE 36.—*Monthly operations of Eldred drainage pumping plant, 1925 to 1930*

DIESEL UNIT

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Fuel oil or coal used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours [1]	Overall efficiency	Average load on engine
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
January	0.60	0.96	745	2.94	19,790	1,246	35.5	26.6	11	100
February	1.37	2.14	1,661	5.13	48,880	3,080	39.3	29.5	18	100
March	2.60	2.32	1,800	6.17	56,170	2,688	31.7	23.8	27	76
April	1.68	1.26	977	4.64	28,810	1,414	30.7	23.0	21	78
May	.85	.85	659	2.97	18,630	585	18.8	14.1	22	50
June	3.61	.41	319	3.80	10,440	358	23.8	17.8	22	54
July	2.60	.40	307	3.12	9,440	422	29.2	21.9	15	71
August	3.46	.12	90	2.76	2,690	146	34.4	25.9	11	87
September [2]	2.36									
October	4.98	.33	258	3.26	7,630	390	32.1	24.0	14	81
November	3.10	1.20	928	2.74	27,700	1,268	29.0	21.7	13	73
December	1.18	.57	443	2.62	17,990	633	30.3	22.7	12	56
Total or average	28.39	10.56	8,187	4.31	248,170	12,230	31.7	23.8	19	78

[1] Engine efficiencies assumed as 69.3 to 75 per cent for Diesel units and 80 to 90 per cent for steam units.
[2] Gravity drainage obtained.

TABLE 36.—*Monthly operations of Eldred drainage pumping plant, 1925 to 1930*—Continued

DIESEL UNIT—Continued

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Fuel oil or coal used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity							
1926	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*	*Indicated horsepower-hours*	*Brake horsepower-hours*	*Per cent*	*Per cent*
January	0.84	0.56	436	2.44	12,630	498	26.1	19.6	13	68
February	2.34	1.18	911	3.78	27,860	1,195	27.9	20.9	19	68
March	2.69	1.65	1,276	5.69	41,060	1,804	29.9	22.4	26	70
April	3.45	3.74	2,900	10.20	103,210	4,463	31.6	23.7	44	67
May	1.66	1.42	1,098	6.12	33,850	1,520	29.3	22.0	29	71
June	3.85	.55	429	5.47	13,310	739	36.6	27.4	20	88
July	2.44	.22	169	2.28	4,880	229	28.8	21.6	11	75
August	4.08	.04	32	1.03	880	42	27.8	20.9	5	76
September	11.49	4.51	3,493	11.71	136,100	5,623	34.2	25.6	47	66
October	4.72	6.14	4,761	11.88	170,630	6,975	31.1	23.3	52	65
November	3.46	4.71	3,653	9.62	123,750	5,940	34.5	25.9	38	76
December	1.34	2.50	1,938	9.26	65,670	3,113	34.1	25.6	37	75
Total or average	42.36	27.22	21,096	9.55	733,830	32,141	32.2	24.2	41	70

STEAM UNITS

1926						*Pounds*				
April		0.32	249	8.41	10,160	55,000	30.1	24.1	38	59
September		.86	669	9.11	41,590	211,300	43.0	34.4	29	55
October		2.04	1,583	11.48	99,940	570,800	49.1	39.3	32	62
November		.74	575	7.58	23,340	129,900	30.8	24.6	34	61
December		.61	474	9.52	21,380	135,700	39.0	31.2	34	69
Total or average		4.57	3,550	9.92	196,410	1,102,700	42.3	33.9	32	61

DIESEL UNIT

1927						*Gallons*				
January	1.47	1.99	1,542	5.48	46,310	2,060	32.0	23.5	24	78
February	.84	3.21	2,489	10.04	87,060	4,294	35.0	25.0	39	72
March	6.02	4.12	3,196	9.36	108,250	6,408	34.2	24.6	38	72
April	10.37	5.30	4,111	12.41	162,130	9,346	38.2	27.0	45	68
May	5.51	4.74	3,676	11.39	137,750	7,560	36.8	26.1	42	70
June	3.57	3.59	2,781	15.54	141,060	7,775	46.9	32.5	46	64
July	4.44	.61	473	4.71	14,000	745	31.7	23.4	20	79
August	4.21	.90	699	1.68	19,310	1,149	30.8	23.0	8	83
September	4.09	.23	178	1.78	4,940	300	30.9	23.1	8	83
October	3.57	2.09	1,622	6.77	50,380	2,495	32.5	23.6	29	76
November	5.15	1.97	1,528	3.96	44,060	2,361	30.8	22.6	18	78
December	2.13	3.35	2,593	8.53	85,060	4,643	33.5	24.2	35	74
Total or average	51.37	32.10	24,888	9.74	900,310	49,136	36.0	25.8	37	71

STEAM UNITS

1927						*Pounds*				
March		2.15	1,665	9.49	72,750	467,400	28.3	22.6	46	52
April		3.91	3,030	12.36	176,300	1,134,200	37.7	30.2	45	52
May		3.10	2,402	10.76	119,970	771,000	32.3	25.9	46	52
June		.21	165	15.76	24,720	158,800	97.0	77.6	22	52
November		.02	12	4.50	340	2,200	18.3	15.0	34	53
December		.26	203	6.72	7,090	45,600	22.7	18.1	41	52
Total or average		9.65	7,477	11.12	401,170	2,579,200	34.8	27.8	44	52

TABLE 36.—*Monthly operations of Eldred drainage pumping plant, 1925 to 1930*—Continued

DIESEL UNIT—Continued

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horsepower-hours operated	Fuel oil or coal used	Power used per acre-foot: Indicated horsepower-hours	Power used per acre-foot: Brake horsepower-hours [1]	Overall efficiency	Average load on engine
1928	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
January	1.25	2.18	1,690	6.49	51,940	3,440	32.1	23.4	28	76
February	1.57	.95	737	6.86	22,870	1,520	32.3	23.5	29	76
March	1.44	1.52	1,179	5.59	35,310	1,760	31.7	23.2	24	78
April	4.49	2.71	2,101	8.31	68,750	3,430	33.4	24.1	34	74
May	3.50	1.64	1,269	5.37	37,810	2,090	31.6	23.1	23	78
June	9.38	2.11	1,635	4.87	48,250	2,320	31.5	23.2	21	78
July	2.50	2.26	1,749	5.42	52,190	2,510	31.7	23.3	23	78
August	3.78	1.21	942	4.46	27,560	1,200	31.4	23.1	20	79
September	2.95	1.23	955	3.20	27,130	1,210	31.0	23.0	14	81
October	5.04	1.46	1,130	3.11	32,060	1,700	31.0	23.0	14	81
November	2.19	1.20	930	6.34	28,940	1,540	32.4	23.5	27	76
December	1.88	1.48	1,150	5.23	34,190	1,820	31.5	23.1	23	78
Total or average	39.97	19.95	15,467	5.63	467,000	24,540	31.9	23.3	24	77

STEAM UNITS

1928						*Pounds*				
January	-------	0.06	50	6.50	1,650	11,700	24.6	22.2	36	67
February	-------	1.51	1,167	8.89	42,650	303,900	27.4	24.6	45	67
April	-------	.63	485	5.72	15,630	110,800	24.0	21.6	33	67
June	-------	.14	109	4.67	3,430	24,100	23.2	20.9	28	66
August	-------	.03	22	2.23	680	4,600	21.8	19.5	14	63
October	-------	.07	53	3.38	1,690	10,900	21.7	19.6	21	62
Total or average	-------	2.44	1,886	7.53	65,730	466,000	26.0	23.4	40	67

DIESEL UNITS

1929						*Gallons*				
January	3.34	1.96	1,517	5.73	45,750	2,730	32.0	23.7	25	78
February	.56	1.15	895	5.56	26,830	1,610	32.0	23.7	24	79
March	5.44	3.56	2,760	12.85	120,870	6,620	42.6	30.3	41	69
April	4.53	3.70	2,867	16.57	162,220	8,420	52.3	36.6	44	65
May	9.11	5.14	3,985	13.52	190,920	10,700	47.8	34.4	39	72
June	6.63	2.94	2,277	9.42	79,000	4,570	35.6	25.6	36	74
July	4.29	1.94	1,504	8.81	50,440	2,900	34.2	24.6	35	73
August	2.35	1.11	860	4.39	25,060	1,520	31.5	23.3	19	80
September	2.84	.45	351	2.08	9,750	610	30.7	23.0	9	83
October	4.32	.93	721	2.37	20,170	1,250	30.9	23.2	11	83
November	1.43	1.36	1,054	2.55	29,560	1,830	30.9	23.1	11	82
December	.98	.99	771	2.40	21,560	1,340	30.8	23.1	11	83
Total or average	45.82	25.23	19,562	10.02	782,130	44,100	40.1	28.9	34	72

STEAM UNIT

1929						*Pounds*				
March	-------	0.87	674	11.62	29,310	175,900	36.6	32.2	44	74
April	-------	.24	183	16.08	10,550	67,200	51.5	45.4	43	79
May	-------	1.73	1,343	13.03	61,940	383,400	40.1	35.2	45	76
June	-------	.01	10	9.00	330	1,900	27.0	24.0	46	73
Total or average	-------	2.85	2,210	12.84	102,130	628,400	39.9	35.1	44	76

TABLE 36.—*Monthly operations of Eldred drainage pumping plant, 1925 to 1930*—Continued

DIESEL UNITS

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Fuel oil or coal used	Power used per acre-foot		Over-all efficiency	Average load on engine
		Run-off depth	Quantity							
1930 [3]	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*	*Indicated horsepower-hours*	*Brake horsepower-hours*	*Per cent*	*Per cent*
January	3.37	2.36	1,827	5.62	55,130	2,750	31.9	23.3	24	77
February	1.17	2.82	2,182	7.89	70,040	3,370	33.0	23.9	33	74
March	.71	1.85	1,438	7.54	45,810	2,210	32.9	23.8	31	75
April	.79	1.06	822	5.40	24,560	1,230	31.6	23.1	23	77
May	3.10	.88	681	5.99	20,690	1,030	32.0	23.3	26	77
June	4.00	1.17	907	3.30	25,880	1,350	31.0	23.0	15	81
July	.32	.23	176	2.56	4,940	260	30.9	23.0	11	82
August [4]	.44	0								
September [4]	2.85	0								
October [4]	1.80	0								
November [4]	2.87	0								
December [4]	.45	0								
Total or average	21.87	10.37	8,033	6.26	247,050	12,200	32.2	23.5	27	76

[3] Steam unit did not operate in 1930.
[4] No pumping—gravity drainage after July 10, 1930.

The efficiency of all units probably could have been improved by reducing the speeds during low river stages. This would have decreased the load on the engines and probably would have increased their life. The over-all efficiency of unit No. 1 was low, at least partly because the discharge pipe was no larger than the pump connection and consequently the friction losses were large.

Unit No. 1 pumped approximately 85 per cent of the total run-off pumped, although its capacity was only 41 per cent of the plant total of 0.522 inch per 24 hours. The pump efficiency of the unit was very good as compared with that of other plants, as the average power consumption was approximately 25.3 brake horsepower-hours per acre-foot with an average static lift of about 8.35 feet. The average gross consumption of fuel oil was very low, amounting to 0.5 pound per brake horsepower-hour.

COST OF PUMPING

The operating costs for the Diesel and steam units are given separately in Table 37. The cost of pumping with the steam units was 39 per cent of the total costs for the six years, although they pumped only 13 per cent of the total run-off. The average static lift for the steam units was 10.64 feet, and for the Diesel units 8.35 feet.

TABLE 37.—*Operating costs, including fixed charges, for Eldred drainage pumping plant, 1925 to 1930*

DIESEL UNITS

Year	Fixed charges	Fuel oil or coal	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 ..... dollars	4,100	703	1,500	50	120	28	288	6,789
1926 ..... do	4,100	2,202	2,090	434	325	47	180	9,378
1927 ..... do	4,100	2,601	1,937	3,154	840	37	258	12,927
1928 ..... do	4,100	1,113	1,880	2,977	464	125	700	11,359
1929 ..... do	5,844	2,190	1,997	315	343	50	256	11,005
1930 ..... do	[1] 5,844	596	1,523	462	431	176	146	9,178
Average ..... do	4,681	1,568	1,821	1,232	421	77	306	10,106
Per cent of total	46.3	15.5	18	12.2	4.2	0.8	3	100

STEAM UNITS

1925 [2] ..... dollars	2,184						97	2,281
1926 ..... do	2,184	3,378	2,107	57	250	418	165	8,559
1927 ..... do	2,184	7,777	2,173	756	303	37	269	13,499
1928 ..... do	2,184	1,133	896	2,657	62	73	460	7,465
1929 ..... do	1,456	1,388	1,373	199	42	23	111	4,592
1930 ..... do	1,456			267		88	29	1,840
Average ..... do	1,941	2,279	1,092	656	110	106	189	6,373
Per cent of total	30.5	35.8	71.1	10.3	1.7	1.7	2.9	100

[1] Includes allowance for Diesel engine No. 3.
[2] Not operated.

The fixed charges on units No. 2 and No. 3 were recomputed for 1929. When the old engine No. 3 had been abandoned at the end of 1928, the depreciated value of the steam plant was estimated as $20,250, including $6,000 as the value of pump No. 3 with its suction and discharge pipes and the building and other equipment pertaining to it. The difference, $14,250, was taken as the value of steam unit No. 2, for 1929, as shown in Table 2. The cost of installing the new Diesel engine, $11,065, was added to the valuation placed on the old pump and appurtenant equipment to determine the 1929 valuation of unit No. 3. Each of these units then was estimated to have a further life of 17 years.

The average cost of fuel oil was 5.4 cents per gallon. Repairs and supplies in 1927 and 1928 included a general overhauling of engine No. 1, with replacement of many parts. This was the only important repair work done on the engine during the first 10 years of its operation. The average cost of coal used by the steam units was $5.73 per ton, delivered to the plant, which was three-fourths mile from the railroad siding. The repairs and supplies for 1927 and 1928 include the cost of overhauling engine No. 2.

FABIUS DRAINAGE AND LEVEE DISTRICT

The Fabius drainage and levee district, in Lewis and Marion Counties, Mo., is approximately 6½ miles long and 3½ miles wide. Gravity drainage through a concrete sluiceway is obtained nearly all of the time, and the pumping plant is operated only at very high river stages.

The building is a substantial brick structure with solid concrete foundations. It is located on the Fabius River about a mile above

the junction with the Mississippi River. The two pumping units described in Table 1 are arranged so that both pumps may be driven by either engine. The speed of the pumps has varied between 145 and 170 revolutions per minute, except that when both were connected to one engine the speed dropped to about 125 revolutions per minute.

The suction flanges of the pumps are connected by short iron pipes to a concrete suction pipe similar to that at the Banner Special plant. The discharge pipes pass through the levee, which has been used for a road. Traffic over this road, and perhaps settlement of the levee, have deformed the discharge pipes.

OPERATION OF PLANT

Records of the operation of this plant were kept from 1925 to 1928, and are given in Table 38. The yearly run-off pumped varied from only 1.18 inches in 1925 to 17.12 inches in 1927. During 1925 the river stages were low and the gravity sluiceway provided satisfactory drainage practically the whole year. Floods in September and October, 1926, in the spring of 1927, and in November, 1928, taxed the pumping plant to capacity. The river fluctuated a great deal in 1928, and some pumping was done during 10 months of the year.

TABLE 38.—*Monthly operations of Fabius drainage pumping plant, 1925 to 1928*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours	Fuel oil used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours* [1]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
January [2]	0.33									
February [2]	1.90									
March	1.93	0.03	39	0	940	48	22.8	15.9	0	66
April [2]	2.26									
May [2]	1.77									
June	4.41	.31	388	4.07	8,310	508	24.3	17.0	23	79
July	4.62	.56	701	2.29	15,610	813	21.5	15.1	15	68
August [2]	5.14									
September [2]	6.31									
October	4.47	.19	237	2.40	5,000	265	20.8	14.6	16	69
November	2.54	.09	117	3.98	2,750	131	20.8	14.5	26	62
December [2]	2.04									
Total or average	37.72	1.18	1,482	2.85	32,610	1,765	22.1	15.5	18	70
1926										
January [2]	1.34									
February	1.98	.12	152	2.50	3,170	128	14.9	10.5	23	50
March [2]	2.97									
April	3.19	3.75	4,658	3.30	107,810	4,308	16.9	11.8	27	51
May	2.08	.22	274	2.31	9,130	365	23.5	16.5	14	49
June	7.68	1.83	2,271	6.19	67,540	3,729	29.0	20.3	29	68
July [2]	1.81									
August [2]	5.83									
September	11.64	5.54	6,875	7.04	214,250	13,058	34.8	24.3	28	78
October	3.36	3.05	3,782	5.58	133,250	10,009	42.1	29.5	18	84
November [2]	3.23									
December	.91	.07	85	.20	2,500	196	35.6	24.9	1	85
Total or average	46.02	14.58	18,097	5.52	537,650	31,793	30.7	21.5	25	72

[1] Engine efficiencies assumed as 70 per cent.
[2] Gravity drainage.

TABLE 38.—*Monthly operations of Fabius drainage pumping plant, 1925 to 1928*—Continued

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours	Fuel oil used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity							
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*	*Indicated horsepower-hours*	*Brake horsepower-hours*	*Per cent*	*Per cent*
January [2]	1.58									
February	1.25	0.78	973	4.23	24,200	2,230	32.8	22.9	18	92
March	4.29	2.70	3,353	4.21	82,730	7,610	32.6	22.8	18	92
April	6.28	4.52	5,611	6.50	143,830	13,240	33.8	23.7	26	92
May	4.50	4.15	5,156	4.79	116,310	10,705	29.8	20.9	22	92
June	4.83	4.97	6,173	3.47	130,380	12,000	27.9	19.5	17	92
July [2]	3.50									
August [2]	1.52									
September [2]	2.98									
October [2]	4.34									
November [2]	2.56									
December [2]	2.95									
Total or average	40.58	17.12	21,266	4.74	497,450	45,785	30.9	21.6	21	92
1928										
January	.49									
February	1.93	.23	291	3.06	6,000	410	27.6	19.3	15	94
March	.88	.34	423	2.33	8,540	590	27.1	19.0	12	94
April	3.58	1.69	2,102	4.90	46,750	3,180	29.6	20.7	23	93
May	2.10	1.12	1,386	3.64	29,710	2,000	28.3	19.8	18	92
June	5.44	.50	619	2.38	12,620	870	27.3	19.1	12	94
July	1.08	.31	383	2.26	7,770	530	27.2	19.0	11	94
August	4.54									
September	3.22	.16	197	4.81	4,370	300	29.7	20.8	22	94
October	4.14	.67	831	3.55	17,650	1,210	28.5	19.9	17	94
November	5.62	2.42	3,009	4.71	67,360	4,610	30.0	21.0	22	94
December	1.50	.62	773	3.86	16,600	1,140	28.8	20.1	18	94
Total or average	34.52	8.06	10,014	4.05	217,370	14,840	29.0	20.3	19	94

[2] Gravity drainage.

The capacity of the plant probably would have been sufficient if both units could have been used when needed, but on account of their poor condition either one or both units failed during the most severe flood periods. Only one unit could be run during most of the flood of 1927, and in April both units failed and no pumping was done for about 10 days. During the flood of November, 1928, one unit could not be operated, and considerable land was flooded. The maximum 24-hour run-off pumped was 0.512 inch. The plant operated usually against lifts less than 5 feet. The monthly average lifts ranged from 0 to 7.04 feet. However, as the elevation of the suction bay was not held down to normal during any of the floods, the maximum lifts were less than if the plant had been able to control the water. The suction-bay level was usually held below 7 to 8 feet if possible. Stages of 11.5 to 12.7 feet were reached in October, 1926, in June, 1927, and in November, 1928.

Gravity drainage was obtained when the stage of the discharge bay fell below 8 feet. In June and in September and October, 1926, the river reached 18 feet. It was high all during the spring of 1927 and reached 17.3 feet in June. The maximum stage recorded was 20 feet in November, 1928.

The average gross consumption of fuel oil was 0.7 pound during 1927. The engines were overhauled during 1927 and 1928, and in the latter year the average consumption was 0.51 pound per brake horse-

power-hour. The pump efficiencies were very good, as only 21.1 brake horsepower-hours per acre-foot were required at the average lift of 4.83 feet.

COST OF PUMPING

The cost data for this plant, shown in Table 39, were obtained near the end of its useful life and undoubtedly are greater than if obtained when the plant was new. Moreover, the engines were of an experimental type; therefore nearly all repair parts had to be made specially and were expensive. The engines were designed to run at 200 revolutions per minute, but could not be operated above 170 revolutions per minute. The plant seldom had received proper care and maintenance before 1927 and was in poor condition. Because of these unrepresentative conditions, the data for this plant have not been used in computing average costs for groups. (Pp. 86–91.)

TABLE 39.—*Operating costs, including fixed charges, for Fabius drainage pumping plant, 1925 to 1928*

Year	Fixed charges	Fuel oil	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 ..... dollars	5,623	140	1,725	650	50	80	437	8,705
1926 ..... do	5,623	2,915	2,021	611	1,177	157	680	13,184
1927 ..... do	5,623	3,272	1,566	8,522	1,564	22	1,190	21,759
1928 ..... do	5,623	950	2,400	11,955	747	198	583	22,456
Average ..... do	5,623	1,819	1,928	5,435	884	114	723	16,526
Per cent of total	34	11	11.7	32.9	5.3	0.7	4.4	100

After the plant failed to operate during the height of the 1927 flood, both engines were completely overhauled, at a cost of over $20,000 during the following two years. Had this large cost been foreseen, probably new equipment would have been installed. The cost of lubricating oil for this plant was extremely high, and averaged nearly half that of the fuel oil. An appreciable amount of the oil was used, however, in the overhauling of the plant.

The fuel oil was hauled from a railroad siding about 4 miles distant, and the average cost was 7.7 cents per gallon delivered to the plant.

MAUVAISTERRE DRAINAGE AND LEVEE DISTRICT

The Mauvaisterre drainage and levee district, on the east side of the Illinois River, surrounds the town of Naples. The land is comparatively high, and most of it was cultivated before the district levees were built, being subject to overflow only at very high stages of the river. The construction of dams in the river and the building of levees by other districts have tended to make overflow of this land more frequent. The levees, ditches, and pumping plants of the Mauvaisterre district were constructed in 1925 and 1926. When the river drops below flood stage gravity drainage is obtained by opening a concrete culvert through the levee

The building is of hollow concrete blocks on a concrete foundation and contains the single pumping unit described in Table 1. The Diesel engine has a governor by which its speed can be changed while running, from 190 to 257 revolutions per minute. Such a wide

range of speed is especially desirable for a plant like this, which has to pump against a wide range of lifts.

OPERATION OF PLANT

Record of the operation of this plant was started April 10, 1927, and continued through 1929. The data given in Table 40 are representative of the pumping requirements for districts that obtain gravity drainage when the river is below flood stage. In years of extreme floods the amount of pumping is very large, but during dry years the pumping may be negligible in amount.

TABLE 40.—*Monthly operations of Mauvaisterre drainage pumping plant, 1927 to 1929*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Fuel oil used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				Indicated horsepower-hours	Brake horsepower-hours [1]		
1927	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
April [2]	6.60	2.75	1,644	6.46	49,200	2,840	34.0	25.5	26	85
May	5.83	3.41	2,041	6.06	60,930	3,400	32.8	24.6	25	82
June	3.36	3.53	2,112	8.66	69,120	3,840	35.9	27.0	33	82
July	4.75	.13	75	3.09	2,280	120	30.3	22.7	14	75
August [3]	2.32									
September [3]	2.96									
October	3.59	.20	120	3.00	3,250	190	31.9	23.9	13	88
November [3]	3.99									
December	2.23	.16	97	3.10	2,630	160	32.2	24.1	13	89
Total or average	35.63	10.18	6,089	6.93	187,410	10,550	34.2	25.6	28	83
1928										
January	.44	.39	231	2.01	6,170	370	31.6	23.7	9	89
February	1.59	.61	365	2.34	9,970	570	31.0	23.2	10	85
March [3]	.97									
April	3.63	.37	222	1.79	6,030	340	29.9	22.4	8	82
May [3]	2.94									
June [3]	5.39									
July [3]	4.44									
August [3]	4.29									
September [3]	4.09									
October [3]	3.55									
November [3]	3.04									
December [3]	1.79									
Total or average	36.16	1.37	818	2.10	22,170	1,280	30.8	23.1	9	85
1929										
January	3.58	.38	230	2.00	6,500	370	30.9	23.0	9	82
February	.38	.30	180	2.00	5,000	290	30.6	22.8	9	82
March	4.13	1.22	730	6.00	21,600	1,310	34.0	25.5	24	86
April	4.95	1.50	897	8.00	27,950	1,740	36.9	27.6	30	89
May	6.38	3.21	1,920	6.36	57,510	3,540	34.9	26.2	25	88
June	3.36	1.24	742	3.44	20,980	1,230	31.6	23.7	15	84
July	4.22	.87	523	5.61	15,460	920	33.5	25.1	23	85
August [3]	2.87									
September [3]	2.58									
October [3]	5.45									
November [3]	1.80									
December [3]	1.20									
Total or average	40.90	8.72	5,222	5.76	155,000	9,400	34.2	25.6	23	86

[1] Engine efficiencies assumed as 75 per cent.
[2] Records commenced Apr. 10
[3] Gravity drainage.

More pumping was done in the spring of 1927 than in either of the two succeeding years. Besides the run-off recorded, the plant probably pumped about 7 inches in 1927 before the records were commenced. The total pumped that year was thus approximately 17 inches, whereas the amount pumped was only 1.37 inches in 1928 and 8.72 inches during 1929.

The capacity of this plant is less than that of most of the plants studied in Illinois, but comparatively little seepage during river floods needs to be pumped. The maximum 24-hour run-off pumped was only 0.171 inch in 1927, but the plant was unable to control the elevation of water in the suction bay that year. The water was under very good control during 1928 and 1929, and 24-hour operation of the plant was necessary for only a few days in 1929.

The plant usually operated against lifts less than 6 feet; the maximum monthly lift was 8.66 feet. Had the plant been of sufficient capacity to control the water, greater lifts probably would have resulted during the flood of 1927.

The plant was fairly efficient, as the power consumption averaged 25.5 brake horsepower-hours per acre-foot and the gross fuel oil consumption was only 0.48 pound per brake horsepower-hour.

Tests indicated, however, that at the lifts against which this plant operated, considerable saving of fuel oil was possible by reducing the pump speed. The brake horsepower-hours per acre-foot pumped dropped from 27 to 17.8 and from 31.4 to 20.8 when the speed was reduced from approximately 250 to 190 revolutions per minute during tests in 1927. However, the operator at this plant was paid by the hour. With fuel oil costing 7 cents per gallon and the operator being paid 40 cents per hour, the most economical speed would be approximately 220 revolutions per minute. Reducing the speed to this extent probably would also reduce the wear on the engine.

COST OF PUMPING

The operating expenses are given in Table 41. The average cost of the fuel oil was 6.7 cents per gallon. The operator was employed only when pumping was necessary, and paid $0.40 per hour. Considerable repair work was necessary in 1928, to prevent the foundations from being undermined. The engine was overhauled after the pumping season of 1929, and the repair expenditures that year were largely for engine parts. The miscellaneous costs in 1928 include fire insurance, which is comparatively expensive for this type of plant.

TABLE 41.—*Operating costs, including fixed charges, for Mauvaisterre drainage pumping plant, 1927–1929*

Year	Fixed charges	Fuel oil	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1927 ---------- dollars	1,758	732	1,068	189	219	00	210	[1] 4,176
1928 ---------- do	2,412	89	249	425	30	526	158	3,889
1929 ---------- do	2,412	603	679	517	184	36	149	4,580
Average for 2.729 years ---------- do	2,412	522	731	414	159	206	189	4,633
Percent of total	52.1	11.3	15.8	8.9	3.4	4.4	4.1	100

[1] For period Apr. 10, 1927, to Dec. 31, 1927.

McGEE CREEK DRAINAGE AND LEVEE DISTRICT

The McGee Creek drainage and levee district extends along the west side of the Illinois River for 7 miles. From a width of 4½ miles at the middle, it narrows to about 1 mile wide at each end.

The original steam plant, at the south end of the district, began operating in 1908 and was abandoned in 1926. The second steam plant, constructed about 1915 near the center of the district, is described in Table 1 as unit No. 5. It is used now only for stand-by service. It is operated at from 180 to 190 revolutions per minute at medium heads and at about 200 revolutions per minute at high heads, and has a maximum speed range of from 168 to 225 revolutions per minute. It was housed in a brick building on concrete foundations, but the floods of 1926 and 1927 washed out the west wall of this building, besides doing other damage. The 225-horsepower vertical type water-tube boiler is hand fired, and like the remainder of the steam-plant equipment is in very poor condition.

The four semi-Diesel units described in Table 1 are housed in a concrete block building. The machinery rests on a reinforced concrete floor 24 inches thick, under which several concrete buttresses go down to solid ground, but no piling was driven beneath it. The foundation is entirely inclosed by sheet piling to prevent sand escaping, and no settlement has been noted, but this method of construction is not to be generally recommended. The oil-engine plant was constructed adjacent to the second steam plant in 1926, but the district was flooded from the fall of that year until the following summer. By November, 1927, the plant had been overhauled and began operating. The pumps operate at speeds of 320 and 355 revolutions per minute.

OPERATION OF PLANT

Records of operation were kept at this plant during the period 1928 to 1930, and are summarized in Table 42. Owing to the large capacity and economy of the oil-engine plant, the steam unit has been used very infrequently. A rain of 2.15 inches on July 31 and 4.08 inches on August 1, 1928, caused all five units to be put into operation, and the run-off pumped on August 1 was 0.328 inch for the semi-Diesel units and 0.041 inch for the steam unit. After the oil-engine plant was damaged by fire on October 12, 1928, all pumping was done with the steam unit until one of the other units was put into operation on November 20. The plant held the water under good control in 1929, except when its fuel-oil supply was exhausted. The water level in the drainage ditches fluctuated greatly because of a large accumulation of silt in them and consequent lack of storage capacity. Little pumping was necessary in 1930.

TABLE 42.—*Monthly operations of McGee Creek drainage pumping plant, 1928 to 1930*

SEMI-DIESEL UNITS

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horse-power-hours operated	Fuel oil or coal used	Power used per acre-foot: Indicated horse-power-hours [1]	Power used per acre-foot: Brake horse-power-hours [1]	Overall efficiency	Average load on engine
1928	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
January	0.34	1.70	2,229	9.22	79,940	6,450	45.7	34.3	28	96
February	1.42	1.61	2,110	9.57	80,380	5,990	43.4	32.6	30	86
March	.81	.81	1,065	7.37	38,150	3,220	41.2	30.9	24	86
April	4.05	1.55	2,033	8.66	74,410	5,350	43.2	32.4	28	88
May	3.55	.83	1,085	6.68	37,030	2,850	42.7	32.0	22	94
June	5.60	.73	954	5.92	32,010	2,570	42.2	31.6	19	94
July	3.67	.68	891	7.43	31,210	2,050	43.2	32.4	24	92
August	7.58	1.71	2,235	5.43	76,580	5,050	40.2	30.2	18	88
September	4.19	.41	530	4.43	18,470	1,450	36.7	27.5	17	79
October	3.04	.16	203	3.54	6,750	1,140	37.9	28.4	13	86
November	4.07	.54	703	4.72	23,590	1,590	40.2	30.2	16	90
December	2.91	1.64	2,149	5.56	73,780	5,000	40.4	30.3	19	88
Total or average	41.23	12.37	16,187	7.18	572,300	42,710	42.2	31.6	23	89

STEAM UNIT

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horse-power-hours operated	Fuel oil or coal used	Power used per acre-foot: Indicated horse-power-hours [1]	Power used per acre-foot: Brake horse-power-hours [1]	Overall efficiency	Average load on engine
1928						*Pounds*				
March	0.20		24	5.54	960	6,600	35.4	30.0	22	75
May	.08		110	5.60	4,600	31,800	37.2	31.6	21	76
July	.04		56	3.80	2,250	15,600	35.7	30.4	15	76
August	.08		108	4.66	4,390	30,400	36.1	30.7	18	76
October	.39		516	2.62	20,250	140,100	34.9	29.7	10	76
November	.61		792	3.41	31,580	218,500	35.4	30.1	13	76
December	.14		.179	7.40	8,010	55,500	39.8	33.8	26	76
Total or average	1.36		1,785	3.83	72,040	498,500	35.9	30.5	15	76

SEMI-DIESEL UNITS

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horse-power-hours operated	Fuel oil or coal used	Power used per acre-foot: Indicated horse-power-hours [1]	Power used per acre-foot: Brake horse-power-hours [1]	Overall efficiency	Average load on engine
1929						*Gallons*				
January	4.38	1.91	2,492	7.66	87,680	6,000	44.0	33.0	24	94
February	.61	1.06	1,393	7.89	49,350	3,330	43.7	32.8	25	92
March	3.69	4.88	6,385	12.06	241,050	17,100	50.2	37.7	33	100
April	4.51	3.62	4,741	15.53	201,760	14,200	54.4	40.8	39	96
May	5.70	4.17	5,455	13.77	212,510	15,900	53.0	39.7	36	102
June	2.92	1.38	1,810	11.42	66,220	4,960	49.8	37.4	32	102
July	5.54	1.54	2,012	12.23	75,250	5,650	50.8	38.1	33	102
August	1.98	.44	574	6.19	19,650	1,310	41.7	31.3	20	91
September	2.65	.19	254	3.37	8,370	530	38.4	28.8	12	87
October	3.04	.40	524	3.74	17,210	1,130	39.4	29.6	13	90
November	4.07	.57	742	3.95	23,790	1,650	40.8	30.6	13	95
December	2.91	.44	571	3.32	18,360	1,240	39.8	29.9	11	93
Total or average	42.00	20.60	26,953	11.59	1,021,220	73,000	49.6	37.2	32	98

STEAM UNIT

Year and month	Rainfall	Water pumped: Run-off depth	Water pumped: Quantity	Average static lift	Rated horse-power-hours operated	Fuel oil or coal used	Power used per acre-foot: Indicated horse-power-hours [1]	Power used per acre-foot: Brake horse-power-hours [1]	Overall efficiency	Average load on engine
1929						*Pounds*				
March	0.37		482	11.56	25,030	130,000	48.0	40.8	33	79
May	.22		288	11.79	14,620	80,000	49.0	41.6	33	82
Total or average	.59		770	11.65	39,650	210,000	48.4	41.1	33	80

[1] Engine efficiencies assumed as 75 per cent for semi-Diesel units and 85 per cent for steam units.

TABLE 42.—*Monthly operations of McGee Creek drainage pumping plant, 1928 to 1930*—Continued

SEMI-DIESEL UNITS[2]

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Fuel oil used	Power used per acre-foot		Over-all efficiency	Average load on engine
		Run-off depth	Quantity							
1930	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*	*Indicated horsepower-hours*	*Brake horsepower-hours*	*Per cent*	*Per cent*
January	3.30	0.88	1,153	6.10	37,650	2,540	40.6	30.5	20.6	93.3
February	1.88	1.82	2,378	8.42	81,720	6,050	43.7	32.8	26.5	95.3
March	1.05	2.44	3,193	9.04	109,050	8,530	43.7	32.8	28.4	96.0
April	2.01	.69	902	7.72	31,680	2,340	42.7	32.1	24.8	91.3
May	1.90	.59	776	9.45	28,400	2,000	44.3	33.2	29.3	90.7
June	3.83	.23	296	3.87	9,690	630	38.4	28.8	13.8	88.0
July	.64	.02	29	2.79	930	70	37.2	27.9	10.3	87.3
August	2.40	.00								
September	2.60	.00								
October	1.47	.02	27	1.26	880	100	35.9	27.0	4.8	83.3
November	2.27	.00								
December	.54	.00								
Total or average	23.89	6.69	8,754	8.16	300,000	22,260	43.0	32.3	26.0	94.2

[2] Steam unit did not operate in 1930.

It was found that the pumps should be slowed down to a speed of 320 revolutions per minute in order to save fuel oil when pumping against low and medium lifts. The saving of fuel oil to pump a given quantity of water amounted to 16 per cent as a result of decreasing the speed of pump No. 4 from 340 to 320 revolutions per minute during the tests of September 7, 1928.

The amounts of rainfall for 1928 and 1929 were approximately equal, but in 1928 the river stages were low, and the run-off pumped was only 13.73 inches, while in 1929 the river stages were higher and a greater quantity of seepage increased the run-off to 21.19 inches. The run-off in 1930 amounted to only 6.69 inches. The over-all efficiencies of the semi-Diesel units were comparatively low, partly because of their high belt losses.

COST OF PUMPING

The operating expenses are given in Table 43. The fixed charges for this plant are exceptionally low, due to its small first cost of $110 per horsepower. The costs of the other oil-engine plants built after 1920 were $169 to $231 per horsepower.

TABLE 43.—*Operating costs, including fixed charges, for McGee Creek drainage pumping plant, 1928–1930*

SEMI-DIESEL UNITS

Year	Fixed charges	Fuel oil or coal	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1928 dollars	6,337	2,286	2,006	121	444	79	700	11,973
1929 do	6,337	3,579	2,572	220	518	761	1,106	15,093
1930 do	6,337	1,014	1,740	541	137	452	660	10,881
Average do	6,337	2,293	2,106	294	366	431	822	12,649
Per cent of total	50.1	18.1	16.7	2.3	2.9	3.4	6.5	100

STEAM UNIT

1928 dollars	430	880	284	0	60	0	102	1,756
1929 do	430	439	188	23	20	0	87	1,187
1930 do	430						28	458
Average do	430	440	157	8	27	0	72	1,134
Per cent of total	37.9	38.8	13.9	0.7	2.4		6.3	100

The average cost of fuel oil was 5 cents per gallon, delivered, which was less than for any other plant. The labor cost was somewhat

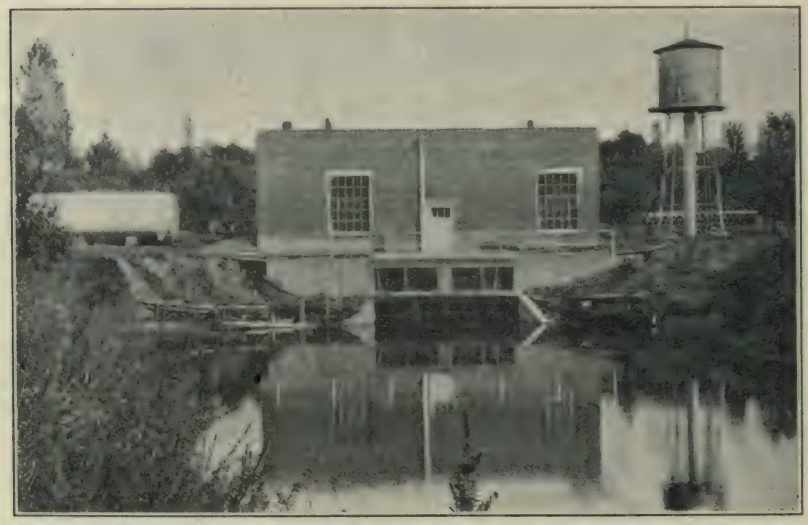


FIGURE 13.—Valley City drainage pumping plant, showing high quality of building, and fuel oil tanks at left

higher than for most of the electric and oil-engine plants, as two operators were generally employed. However, the plant received excellent care, and the cost of repairs was small.

The costs for the steam unit were not great, as its valuation was only $13 per horsepower, and in the two years it pumped only 5 per cent of the total.

VALLEY CITY DRAINAGE AND LEVEE DISTRICT

The Valley City drainage and levee district extends along the west side of the Illinois River for approximately 4½ miles and averages about 1¾ miles in width. It is one of the more recent districts along the Illinois, as pumping was first commenced in January, 1923.

A substantial brick structure housing the two pumping units is described in Table 1 and shown in Figure 13. The speed of these units can be varied only from 245 to 260 revolutions per minute. The manufacturer guaranteed that the engines would operate with a fuel consumption of 0.5 pound of approved oil per brake horsepower-hour at full load, 0.52 pound at three-fourths load, and 0.6 pound at one-half load, and that they would require only 1 gallon of approved lubricating oil per 2,000 rated horsepower-hours. The fuel consumption has been very close to these guarantees, but the gross use of lubricating oil has been somewhat greater.

As at the Green Bay plant, the discharge pipes from both pumps discharge through short sections of iron pipe into a concrete sluiceway which extends horizontally through the levee into the discharge bay. A flap gate at the end of the sluiceway is provided in addition to belt-operated gates at the pumps. A manhole near the outer end of the sluiceway permits inspections and repairs.

OPERATION OF PLANT

Records were kept on this plant from 1925 to 1930, inclusive. The operation data are given in Table 44. The annual run-off pumped ranged from 5.56 to 23.46 inches. The average fuel-oil consumption was comparatively low, 0.52 pound per brake horsepower-hour.

TABLE 44.—*Monthly operations of Valley City drainage pumping plant, 1925 to 1930*

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Fuel oil used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				Indicated horsepower-hours	Brake horsepower-hours [1]		
1925	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
February [2]	0.60	0.77	458	8.90	16,490	1,168	46.6	36.3	26	101
March	3.46	1.59	948	8.39	29,380	2,080	40.1	31.2	29	101
April	2.52	.62	369	8.82	12,240	867	42.9	33.5	28	101
May	2.04	.35	210	6.26	6,980	494	43.0	33.5	20	101
June	3.05	.26	156	6.83	4,550	322	37.7	29.4	25	101
July	3.62	.29	171	6.43	4,910	347	37.0	28.9	24	101
August	3.82	.23	135	6.41	3,810	270	36.5	28.5	24	101
September	4.26	.13	80	5.98	2,300	163	37.3	29.0	22	101
October	5.43	.34	205	6.04	5,640	399	35.5	27.7	23	101
November	2.93	.56	332	5.48	8,980	636	35.0	27.3	22	101
December	.69	.42	251	5.40	6,740	476	34.6	27.0	21	101
Total or average	32.42	5.56	3,315	7.40	102,020	7,222	39.8	31.0	26	101
1926										
January	1.68	.52	312	5.85	7,980	610	35.4	27.7	23	108
February	1.54	.98	587	6.63	15,930	1,050	32.4	25.3	28	93
March	2.79	1.05	628	8.47	17,490	1,128	32.6	25.4	36	91
April	4.20	3.55	2,120	11.22	64,620	3,934	33.6	26.2	46	86
May	2.10	.91	540	10.86	16,130	1,228	41.1	32.0	36	107
June	5.59	1.03	615	10.83	18,760	1,300	38.2	29.8	39	98

[1] Engine efficiencies assumed as 78 per cent.
[2] Records commenced Feb. 18.

TABLE 44.—*Monthly operations of Valley City drainage pumping plant, 1925 to 1930*—Continued

Year and month	Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Fuel oil used	Power used per acre-foot		Overall efficiency	Average load on engine
		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours*		
1926	*Inches*	*Inches*	*Acre-feet*	*Feet*		*Gallons*			*Per cent*	*Per cent*
July	2.99	0.47	278	7.64	7,760	600	39.0	30.4	27	109
August	5.03	.52	311	6.71	8,590	665	38.6	30.1	24	109
September [3]	12.94	4.02	2,396	5.63	65,780	4,880	36.7	28.6	21	104
Total or average	38.86	13.05	7,787	8.35	223,040	15,395	35.7	27.9	32	97
1927										
February [4]	.96	5.54	3,308	7.20	90,880	6,360	32.6	25.4	30	92
March [5]	6.58	4.07	2,426	11.72	73,300	5,130	35.9	28.0	45	93
October	3.59	1.74	1,037	7.14	28,430	1,990	32.8	25.6	30	93
November	4.45	1.26	754	7.07	20,850	1,460	32.4	25.3	30	91
December	2.23	1.45	864	9.94	24,650	1,720	34.6	27.0	40	94
Total or average	17.81	14.06	8,389	8.77	238,110	16,660	33.7	26.3	36	93
1928										
January	.44	1.65	987	8.94	27,800	1,760	31.6	24.7	39	88
February	1.59	1.45	864	10.77	25,450	1,630	33.4	26.1	44	89
March	.97	.75	450	9.15	12,980	810	31.9	24.9	39	86
April	3.65	1.69	1,006	10.17	29,850	1,860	32.8	25.6	42	86
May	3.26	.99	593	8.81	17,700	1,060	31.7	24.7	38	83
June	6.47	.91	543	7.41	15,020	920	30.1	23.5	34	85
July	4.61	.72	431	10.00	12,310	790	32.6	25.4	42	89
August	3.74	1.08	642	8.09	17,700	1,110	30.7	24.0	36	87
September	4.55	.75	449	6.22	12,210	740	29.2	22.7	29	84
October	3.91	.99	593	5.64	16,060	960	28.7	22.4	27	83
November	3.17	1.79	1,066	6.60	29,030	1,770	29.4	22.9	31	84
December	1.79	1.37	819	8.94	22,980	1,460	31.6	24.7	39	88
Total or average	38.15	14.14	8,443	8.50	239,090	14,870	31.2	24.4	37	86
1929										
January	3.58	2.00	1,191	8.98	33,810	2,180	31.7	24.7	39	87
February	.38	1.11	660	9.27	19,130	1,220	31.9	24.9	40	86
March	4.13	4.54	2,708	14.19	88,350	5,930	37.9	29.6	51	91
April	4.95	4.03	2,403	17.98	84,120	5,970	43.1	33.6	57	96
May	6.38	4.56	2,719	17.32	96,460	6,640	42.4	33.0	56	93
June	3.36	2.05	1,222	13.87	42,220	2,640	37.4	29.2	51	84
July	4.22	1.96	1,172	13.94	36,690	2,510	37.0	28.9	52	92
August	2.87	.72	430	8.61	11,650	770	31.1	24.3	38	90
September	2.58	.34	203	6.10	5,390	340	28.8	22.5	29	85
October	5.45	.66	391	6.02	11,190	660	29.1	22.7	28	79
November	1.80	.86	512	6.69	13,200	870	29.3	22.8	31	89
December	1.20	.63	378	7.41	11,780	670	30.6	23.9	33	77
Total or average	40.90	23.46	13,989	13.75	453,990	30,400	37.6	29.4	50	90
1930										
January	3.68	1.19	713	9.43	21,880	1,500	32.2	25.1	40.3	81.8
February	1.99	3.42	2,043	11.34	60,530	4,550	34.0	26.5	45.8	89.5
March	.82	1.72	1,025	13.07	31,630	2,420	36.1	28.1	49.7	91.2
April	1.27	.83	498	11.10	16,340	1,110	34.1	26.6	44.7	81.0
May	1.61	.95	566	11.63	16,120	1,270	34.3	26.8	46.5	94.0
June	4.14	.57	340	6.82	8,710	660	29.5	23.0	31.7	89.8
July	.46	.30	179	4.69	4,550	320	27.6	21.5	23.3	84.6
August	1.79	.04	27	4.07	690	50	26.7	20.7	21.0	81.2
September	2.41	.13	76	4.05	2,150	140	27.4	21.3	20.3	75.3
October	1.28	.14	84	3.79	2,360	150	27.3	21.3	19.1	75.8
November	2.14	.15	87	2.84	2,500	150	26.4	20.6	14.7	71.6
December	.30	.17	100	3.28	2,770	180	26.8	20.9	16.8	75.5
Total or average	21.89	9.61	5,738	10.43	170,230	12,500	33.3	25.9	43.1	87.4

[3] Plant flooded Sept. 16.
[4] Pumping resumed Feb. 11.
[5] Plant flooded Mar. 20; pumping resumed Oct. 6.

The diversion levee of the south fork of McGee Creek broke on September 8, 1926, after 5.28 inches of rain on the night of September 7, and a large volume of water poured into the district for 12 hours. Bags of sand were piled around the station and held out 2 feet of water. Another heavy rain on September 15 turned the creek again into the district. Next morning the water was 4 feet deep around the pump house and 8 feet above the pump house floor, and could not be held out longer. Pumping could not be resumed until February 11, 1927. The levee broke again March 20, 1927, flooding the district and the plant and no further pumping was done until October 6, 1927. Because of these abnormal flood conditions the operation records for 1926 and 1927 are of limited value; however, the amount of water pumped each year probably was slightly greater than the average, so the operating expenses may be considered fairly typical for the plant.

COST OF PUMPING

The first cost of the Valley City plant was high, $231 per installed horsepower. The annual fixed charges consequently were large, and amounted to 60.1 per cent of the average total cost of pumping. Probably a less expensive building would have served the district satisfactorily.

The cost data, given in Table 45, were obtained when the plant was comparatively new. Repairs cost very little except during 1929 and 1930, when the engines were overhauled, but probably will become increasingly more expensive. The cost of fuel oil delivered to the plant averaged 6.8 cents per gallon, including transfer by barge about 3 miles from the railroad at Valley City. A large amount of kerosene was used for fuel because several times the plant ran out of fuel oil. The miscellaneous expenses for 1926 include an unusual item of $487 for keeping flood water out of the plant.

TABLE 45.—*Operating costs, including fixed charges, for Valley City drainage pumping plant, 1925–1930*

Year	Fixed charges	Fuel oil	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead charged to pumping plant	Total
1925 ---- dollars	4,310	410	915	44	75	12	141	[1] 5,907
1926 ---- do	4,963	1,234	967	156	226	523	211	[2] 8,280
1927 ---- do	4,963	1,401	1,499	51	201	41	131	[2] 8,287
1928 ---- do	4,963	958	791	121	299	30	479	7,641
1929 ---- do	4,963	2,258	1,233	1,053	490	258	94	10,349
1930 ---- do	4,963	812	800	710	317	142	284	8,028
Average for 3.868 years ---- do	4,963	1,147	967	499	305	114	258	8,253
Per cent of total	60.1	13.9	11.7	6.1	3.7	1.4	3.1	100

[1] For period Feb. 18, 1925, to Dec. 31, 1925.
[2] Plant flooded Sept. 16, 1926; pumping resumed Feb. 11, 1927; plant flooded again Mar. 20, 1927; pumping resumed Oct. 6, 1927. Costs for 1926 and 1927 omitted from averages.

SUMMARY OF OPERATION DATA

The average annual operation data are given in Table 46. The records for any year during which a plant was flooded have been omitted from the averages. Most of the records were obtained during the period 1925 to 1930 when the average rainfall was somewhat in excess of the normal of 34 to 36 inches per year, as shown by long-time records for near-by Weather Bureau stations, and the river stages were high. Data obtained from the Coal Creek plant and several other plants show that the amounts of run-off pumped during this period were greater than normal. This is believed to be due, not so much to the excess in average rainfall, as to the extremely heavy seepage resulting from floods along the Illinois in 1926 and 1927 and along the Mississippi in 1929.

TABLE 46.—*Average annual operations of drainage pumping plants*

Plant	Power type	Years of record		Rainfall	Water pumped		Average static lift	Rated horsepower-hours operated	Current, coal, or fuel oil used [1]	Input to motor or engine	Output of motor or engine	Power used per acre-foot		Average over all efficiency	Average load on motors
		Period	Number averaged		Run-off depth	Quantity				*Indicated horsepower-hours*	*Brake horsepower-hours*	*Indicated horsepower-hours*	*Brake horsepower-hours*		
				Inches	*Inches*	*Acre-feet*	*Feet*							*Per cent*	*Per cent*
Banner Special	Electric	1925	1	27.61	8.98	5,061	10.38	180,100	106,900	143,360	128,790	28.3	25.4	50	71
Coal Creek	do	1914–1921; 1923–1930	16	35.11	23.94	15,010	12.14	624,226	463,289	621,273	559,755	41.4	37.3	40	90
Green Bay	do	1925	1	38.31	21.65	25,272	10.67	619,410	578,900	776,290	714,200	30.7	28.3	48	115
Hartwell	do	1929–1930	2	35.80	13.75	14,778	11.65	530,065	345,825	463,750	428,360	31.4	29.0	51	81
Hunt	do	Apr. 18, 1928 through 1930.	2.70	37.17	16.29	21,498	8.53	743,486	456,580	612,231	561,220	28.5	26.1	41	75
Indian Grave	do	1925–1928 and 1930	5	34.23	13.18	23,060	4.74	711,530	549,362	721,964	664,324	31.3	28.8	21	93
Lima Lake	do	1929–1930	2	34.10	26.56	36,834	9.83	1,313,705	880,095	1,180,205	1,073,985	32.0	29.2	42	82
South Beardstown	do	1925–1930	6	37.85	40.48	28,165	15.35	1,011,792	815,863	1,094,070	976,775	38.8	34.7	54	96
Henderson County	do	May 14, 1928 through 1930.	2.63	40.24	30.95	57,772	6.67	2,103,698	1,078,322	1,446,044	1,302,365	25.0	22.5	37	62
Total or average			38.33	35.60	21.75	25,272	9.45	870,890	586,126	784,360	712,197	31.0	28.2	42	82
Bay Island	Steam	1925–1930	6	38.94	18.21	78,895	7.17	2,140,982	3,118.4	1,934,453	1,702,317	24.5	21.6	40	79
Crane Creek	do	Feb. 10, 1925 through 1930.	5.89	39.53	20.38	10,577	12.44	432,199	834.6	333,974	297,457	31.6	28.1	54	69
Henderson County	do	Mar. 1, 1926–May 13, 1928.	2.20	39.67	35.64	66,533	5.96	2,275,404	3,448.4	1,105,118	972,509	16.6	14.6	49	43
Total or average			14.09	39.38	24.74	52,002	7.01	1,616,195	2,467.1	1,124,515	990,761	21.6	19.1	45	61
Eldred	Stand-by steam	1925–1930	6	.....	3.25	2,520	10.64	127,573	398.0	91,225	74,977	36.2	29.8	40	59
McGee Creek	do	1928–1930	3	.....	.65	852	6.19	37,230	118.1	33,760	28,697	39.6	33.7	21	77
Scott County	do	1929–1930	2	.....	2.72	2,831	15.24	143,600	237.1	93,305	82,110	33.0	29.0	63	57
Total or average			11	.....	2.21	2,068	12.13	102,801	251.1	72,763	61,928	35.2	29.9	47	60
Eldred	Diesel	1925–1930	6	38.30	20.90	16,206	8.35	563,082	29,058	561,978	409,965	34.7	25.3	33	73
McGee Creek	Semi-Diesel	1928–1930	3	35.71	13.22	17,298	9.63	631,167	45,990	798,900	599,180	46.2	34.6	29	95
Scott County	do	1929–1930	2	31.57	11.09	11,553	13.65	472,935	34,370	580,795	435,610	50.3	37.7	37	92
Total or average			11	35.19	15.07	15,019	10.21	555,728	36,473	647,224	481,585	43.1	32.1	33	87
Fabius	Diesel	1925–1928	4	39.71	10.24	12,715	4.83	321,270	23,546	383,550	268,423	30.2	21.1	22	84
Mauvaisterre	do	Apr. 10, 1927 through 1929.	2.73	41.29	7.43	4,444	6.10	133,595	7,779	150,887	113,148	34.0	25.5	25	85
Valley City	Semi-Diesel	Feb. 18–Dec. 31, 1925 and 1928–1930.	3.87	34.48	13.64	8,140	11.07	249,568	16,813	237,764	224,452	35.4	27.6	43	90
Total or average [2]			6.60	37.88	10.54	6,292	9.31	191,582	12,296	219,326	168,800	34.9	26.8	37	88

[1] Kilowatt-hours of electric current, tons of coal, or gallons of fuel oil.

[2] Fabius plant data omitted from average because costs are not representative.

The average operation records for the group of nine electric plants, as shown in Table 46, are believed to represent typical conditions. The operation data for these plants total 38 years of plant operation during which the average rainfall amounted to 35.6 inches and the average run-off to 21.75 inches. The average lift for this group of plants was 9.45 feet and the over-all efficiency 41.8 per cent. The run-off pumped varied greatly, from 8.98 inches for the Banner Special plant (only a single year's record), to 40.48 inches for the South Beardstown plant. The smaller figure probably is much less than normal for that district, and the larger includes a great amount of seepage.

The average rainfall for three steam plants for slightly over 14 plant-years of record was 39.38 inches, indicating that these records were obtained during rather wet years. The average run-off for this group of plants amounted to 24.74 inches, and the average lift was 7.01 feet. The Henderson County steam plant pumped the largest average run-off, amounting to 35.64 inches.

Records for a total of 11 years were obtained from three oil-engine plants that used old steam units for stand-by service. This group of plants did as much as possible of the pumping with the oil engines, and started the steam units only when the run-off became too great for the oil-engine units. The average rainfall for these three plants amounted to 35.19 inches. The average total run-off pumped was 17.28 inches, of which the oil-engine plants pumped 15.07 inches and the stand-by steam plants only 2.21 inches. The average capacity of the oil-engine equipment was 0.212 inch per 24 hours, and that of the stand-by steam equipment 0.213 inch per 24 hours. These records show that a very large portion of the pumping can be done with half of the available plant capacity, when desirable.

The average operations of the plants using only oil-engine equipment shown in Table 46 are based on the records obtained from only two plants, for a period of only 6.6 years. As the Fabius plant records are not considered typical (p.70) they have been omitted from the averages. The average rainfall for the two districts was 37.88 inches, the average run-off 10.54 inches, and the average lift 9.31 feet.

The average over-all efficiencies for the oil-engine plants were 33 per cent for the group that had steam stand-by equipment and 37 per cent for the other group. The average over-all efficiency for the electric plants was 42 per cent. The greater efficiency of the electric plants is partly due to the basic difference in the mechanical efficiencies of electric motors and oil engines. However, the inducement to design the whole plant for high efficiency is greater with electric power than with oil engines, because the saving in cost of current resulting from increased efficiency is greater than the corresponding saving in cost of fuel oil. The average over-all efficiency of the steam plants amounted to 45 per cent.

The brake-horsepower-hour per acre-foot is a convenient unit for comparing the combined efficiencies of the transmission equipment, pumps, and pipes, though it can not be considered independently of the lift. The power consumption of a plant increases with the lift, but less rapidly because the mechanical and hydraulic losses are not proportional to the lift. The data indicate that well-designed plants should not consume more than 20 brake-horsepower-hours per acre-foot at a 5-foot lift, 27.5 at a 10-foot lift, and 35 at a 15-foot lift.

AVERAGE ANNUAL COST OF PUMPING

The average annual total and unit costs of pumping by the plants are shown in Table 47, grouped with respect to the type of power used. The average total costs by groups are the arithmetical averages of the costs for the individual districts, and the average unit costs by groups were computed from the average operating data shown in Table 46. In recent years competition has been principally between oil-engine and electric power. Steam has been regarded less favorably than the other kinds of power, principally because (1) unsatisfactory boiler water and poor maintenance in many instances have resulted in high repair costs; (2) the considerable amount of intermittent labor for firing the boilers often has been difficult to obtain; (3) the costs of labor and fuel are greater than with other power types; and (4) the large waste of fuel in frequent starting and stopping of the plant sometimes has caused the lands to be drained inadequately, through delay in starting the pumps in order to save coal.

TABLE 47.—*Average annual cost of pumping by drainage pumping plants*

Plant	Power type	Years averaged	Fixed charges	Power or fuel	Labor	Repairs and supplies	Lubricating oils and gasoline	Miscellaneous	Overhead	Total operating costs	Unit costs					Annual operation		
											Per rated horsepower	Per brake horsepower-hour	Per acre-foot pumped	Per acre of watershed	Per acre assessed	Plant factor	Run-off pumped	Average static lift
		Number	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Dolls.*	*Cents*	*Dolls.*	*Dolls.*	*Dolls.*	*Per ct.*	*Inches*	*Feet*
Banner Special	Electric	1	2,698	2,935	780	322	20	41	186	6,982	21.48	5.42	1.38	1.03	1.95	4.5	8.98	10.38
Coal Creek	do	16	1,654	9,641	1,294	534	(1)	(1)	425	13,548	45.16	2.42	.90	1.80	2.12	21.3	23.94	12.14
Green Bay	do	1	11,203	7,558	1,200	147	75	20	383	20,586	34.31	2.88	.81	1.47	2.34	13.6	21.65	10.67
Hartwell	do	2	6,470	8,427	1,482	148	56	64	448	17,095	18.83	3.99	1.16	1.33	1.92	5.4	13.75	11.65
Hunt	do	2.70	6,830	9,801	1,372	285	71	36	1,190	19,585	39.17	2.49	.91	1.24	1.29	12.8	16.29	8.53
Indian Grave	do	5	7,154	6,629	1,325	886	199	229	672	17,094	28.49	2.57	.74	.81	.93	12.6	13.18	4.74
Lima Lake	do	2	8,308	15,038	1,315	321	82	364	716	26,144	34.86	2.43	.71	1.57	2.14	16.3	26.56	9.83
South Beardstown	do	6	6,102	13,796	1,622	596	95	199	885	23,295	42.35	2.38	.83	2.79	3.17	20.3	40.48	15.35
Henderson County	do	2.63	6,795	19,136	2,649	298	133	114	2,240	31,365	44.81	2.41	.54	1.40	2.09	21.2	30.95	6.67
Average		38.33	6,357	10,329	1,449	393	81	119	794	19,522	33.60	2.74	.77	1.40	1.84	14.0	21.75	9.45
Per cent of total			32.6	52.9	7.4	2.0	0.4	0.6	4.1	100.0								
Bay Island	Steam	6	7,881	17,203	7,107	2,664	1,148	325	1,991	38,319	38.32	2.25	.48	.74	1.62	19.4	18.21	7.17
Crane Creek	do	5.89	2,037	4,402	2,003	614	181	101	297	9,635	38.54	3.24	.91	1.55	1.92	13.6	20.38	12.44
Henderson County	do	2.37	6,894	14,587	5,974	6,836	1,318	411	1,708	37,728	62.88	[2] 3.93	[2] .57	1.68	2.51	18.5	35.64	5.96
Average		14.26	5,604	12,064	5,028	3,372	882	279	1,332	28,561	46.29	[2] 2.90	[2] .55	1.06	1.96	18.3	24.74	7.01
Per cent of total			19.6	42.2	17.6	11.8	3.1	1.0	4.7	100.0								
Eldred	Steam [3]	6	1,941	2,279	1,092	656	110	106	189	6,373	21.98	8.50	2.53	(4)	(4)	3.0	3.25	10.64
McGee Creek	do.[3]	3	430	440	157	8	27	------	72	1,134	5.04	3.95	1.33	(4)	(4)	1.5	.65	6.19
Scott County	do.[3]	2	1,872	1,185	363	267	98	60	102	3,947	6.86	4.81	1.39	(4)	(4)	1.6	2.72	15.24
Average		11	1,415	1,302	537	310	78	55	121	3,818	10.52	6.17	1.85	(4)	(4)	1.9	2.21	12.13
Per cent of total			37.1	34.1	14.1	8.1	2.0	1.4	3.2	100.0								
Eldred	Diesel [5]	6	4,681	1,568	1,821	1,252	421	77	306	10,106	34.85	2.47	.62	[4] 1.77	[4] 1.95	16.1	20.90	8.35
McGee Creek	Semi-Diesel [5]	3	6,337	2,293	2,106	294	366	431	822	12,649	21.08	2.11	.73	[4] .88	[4] 1.28	11.4	13.22	9.63
Scott County	do [5]	2	2,975	2,151	1,971	286	330	205	216	8,134	55.26	1.90	.72	[4] .98	[4] 1.29	33.2	11.09	13.65
Average		11	4,664	2,004	1,966	604	372	238	448	10,296	29.82	2.15	.69	[4] 1.13	[4] 1.48	15.8	15.07	10.21
Per cent of total			45.3	19.4	19.1	5.9	3.6	2.3	4.4	100.0								
Mauvaisterre	Diesel	2.73	2,412	522	731	414	159	206	189	4,633	38.61	4.09	1.04	.65	1.16	10.8	7.43	6.10
Valley City	Semi-Diesel	3.87	4,963	1,147	967	499	305	114	258	8,253	33.01	3.68	1.01	1.15	1.72	10.2	13.64	11.07
Average		6.60	3,688	834	849	456	232	160	224	6,443	34.83	3.82	1.02	.90	1.46	10.4	10.54	9.31
Per cent of total			57.2	12.9	13.2	7.1	3.6	2.5	3.5	100.0								

[1] Included under supplies and repairs.
[2] Period of operation for Henderson County steam plant, 2.204 years.
[3] These are stand-by units only, auxiliary to oil-engine units shown in following group.
[4] Cost per acre for steam stand-by units included in cost shown for oil engine units.
[5] These are oil-engine units only; steam stand-by units shown in preceding group.

The average size of the electric plants was 581 horsepower and that of the oil-engine equipment in the three plants having steam stand-by units was 347 horsepower. The electric plants drain an average area of 13,935 acres, and the average assessed area supporting the plants amounted to 10,635 acres. The three oil-engine plants drained an average of 12,500 acres, while the average acreage assessed was 9,584. The average run-off pumped by the electric plants was greater, amounting to 21.75 inches; the total run-off for the oil-engine plants amounted to 17.28 inches, of which the oil-engine equipment pumped 15.07 inches.

The average fixed charges for electric plants amounted to 32.6 per cent of the total operating costs. The fixed charges for the Banner Special and Coal Creek plants were comparatively low because these plants were built during the period of lower prices before 1915. The fixed charges of the Green Bay plant are especially high because of unusual construction difficulties. For the remaining plants, which are of good quality construction, the fixed charges did not vary greatly.

The cost of power of the electric plants averaged 52.9 per cent of the total operating costs. The average cost was 1.76 cents per kilowatt-hour, which was much cheaper than could have been obtained about 1920. The rates paid by the Green Bay and Indian Grave districts were unusually low, because these districts made favorable contracts when constructed. The other electric plants use rates now available to any district in that territory. The unit cost of power at the Hartwell plant has been high because the plant had a large run-off capacity, 0.554 inch per 24 hours, and the rates were based accordingly. The commissioners and the engineer of this district feel that the added protection and better drainage have more than paid the extra cost over what a smaller plant would have cost.

The average cost of labor for the electric plants was only $1,449 per year, or 7.4 per cent of the total cost. This is considerably less than the cost for the group of oil-engine plants using steam stand-by equipment, the operation of which is fairly comparable as to plant factor.

The remaining items of cost for the electric plants were less than the cost for any other type of plant, amounting to only 7.1 per cent of the total costs. The repairs and supplies averaged $393 per year, as compared with an average of $604 per year for the group of oil-engine plants using steam stand-by equipment.

Costs for the oil-engine plants using steam for stand-by service have been tabulated as though the oil and steam units were separate plants, because the costs for the oil units are representative of plants with high plant factors.

The fixed charges of these oil-engine units were the largest item of cost, averaging 45.3 per cent of the total cost. The buildings housing these plants are of somewhat cheaper construction than those for the electric plants, but the difference is hardly sufficient to justify much difference in the estimated life of the two groups.

The average cost of fuel oil for these oil-engine plants was only 19.4 per cent of the total operating costs. The low cost of fuel is the principal advantage of oil-engine plants over other types. The average cost for labor for the oil-engine plants amounted to $1,966 or 19.1 per cent of the total operating costs, which was higher than for the electric plants. The oil-engine plant should have a very competent operator, because improper operation may later result in high repair

costs. The repairs on these three oil-engine plants amounted to 5.9 per cent of the total costs. Lubricating oils and gasoline cost about one-fifth as much as the fuel oil. Miscellaneous items, amounting to 2.3 per cent of the total, were somewhat greater than for other types of plants. Overhead expenses did not vary greatly among the different groups of plants.

The total cost of pumping by these three districts includes the cost of the stand-by steam units with that of the oil-engine units. The fixed charges for the steam plants are small, because of the low valuation of these plants when placed in stand-by service. The cost of operating these steam units has been so great that pumping with them was held to a minimum.

The proportion of costs for the two all-oil-engine plants was similar to that of the oil-engine units in the three plants using steam stand-by equipment. The average run-off pumped amounted to only 10.54 inches for the all-oil-engine group, on account of one district having considerable gravity drainage and the other receiving an unusually small amount of seepage. Therefore the fuel cost was a small part of the total, and the fixed charges were by far the largest item of cost.

Fixed charges for the group of all-steam plants amounted to $5,604 per year, only 19.6 per cent of the total cost. These plants were built prior to 1915, when prices were much lower, and if duplicated to-day would cost very much more. The cost of coal amounted to 42.2 per cent of the total. The labor costs also were high, averaging $5,028 per year or 17.6 per cent of the total. All steam plants need at least one and sometimes two firemen in addition to the engineer who must be a competent man. The repairs and supplies for the steam plants were higher than those for any other group, amounting to 11.8 per cent of the total cost. This was because these plants were nearing the end of their useful life when repairs normally would be at their maximum. Lubricating oils cost 3.1 per cent of the total, while the miscellaneous and overhead expenses differed little from the ratios for the other types of plants.

In comparing all-steam plants with other types it should be noted that their average size was 617 horsepower, and the average area drained was 26,877 acres or almost double that for the electric plants. The average acreage assessed was 14,509 acres.

UNIT COSTS OF PUMPING

The unit costs of pumping also are shown in Table 47, with the principal operating factors affecting these costs. The plant factor is the ratio of the work actually done in a stated period, measured in brake horsepower-hours output of the motor or engine, to the brake horsepower-hours that would have been developed had the plant operated continuously at full rated load during the same period. While some expenses, including those for fuel and lubricating oil, are approximately proportional to the amount of pumping, the fixed charges and a part of the labor costs are not affected by the amount of work done. Therefore, the cost per unit of work done by any plant decreases as the plant factor increases.

COST PER BRAKE HORSEPOWER-HOUR

Cost per brake horsepower-hour is the best unit for comparing the cost of power for the different types of plants. Differences in the efficiencies of motors and engines are automatically included and differences in the efficiencies of pumps and pipes are eliminated when comparisons are made on this basis.

The cost per brake horsepower-hour for the Coal Creek plant since 1914, shown in Figure 14 is a typical example of the variation in cost per brake horsepower-hour with the plant factor.

The cost per brake horsepower-hour for the electric plants averaged 2.74 cents, and that for the oil-engine plants having steam stand-by equipment averaged 2.15 cents. The average plant factors for the two groups were 14 and 15.8 per cent, respectively, but this difference would account for only a small part of the difference in the costs.

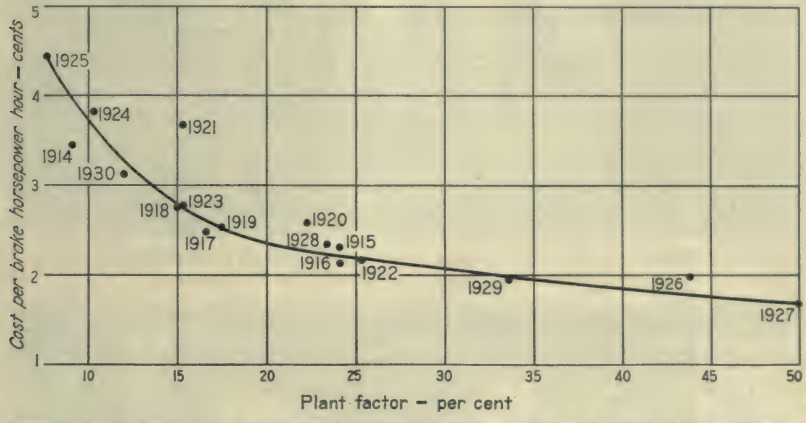


FIGURE 14.—Variation in cost per brake horsepower-hour with plant factor at Coal Creek drainage pumping plant, 1914 to 1930

For the all-oil-engine group, the average cost per brake horsepower-hour was 3.82 cents. This high cost is due to the low plant factor of 10.4 per cent. For the all-steam plants this cost was 2.9 cents at 18.3 per cent plant factor, which is higher than that of either the oil-engine or the electric group at equal plant factor. The cost for the stand-by steam equipment was 6.17 cents at 1.9 per cent plant factor.

The costs per brake horsepower-hour of the individual electric plants did not vary greatly, ranging between 2.38 cents and 2.88 cents for all the plants except the Hartwell and the Banner Special. The high cost for the Banner Special plant was due to the small amount of pumping done, and the high cost for the Hartwell plant was due principally to the large run-off capacity of the plant. The average cost per kilowatt-hour for the group was 1.76 cents. The Green Bay and Indian Grave plants had very favorable power rates, which resulted in average costs of 1.31 and 1.21 cents, respectively, for the periods of record. The average costs per kilowatt-hour for the Banner Special and the Hartwell plants were 2.75 and 2.44 cents, respectively. The average costs for the other plants ranged from 1.69 to 2.15 cents. For all the electric plants studied, power rates were such that the cost per kilowatt-hour decreased as the plant factor increased.

The McGee Creek plant had the lowest cost per brake horsepower-hour of any of the oil-engine plants studied, approximately 2 cents at

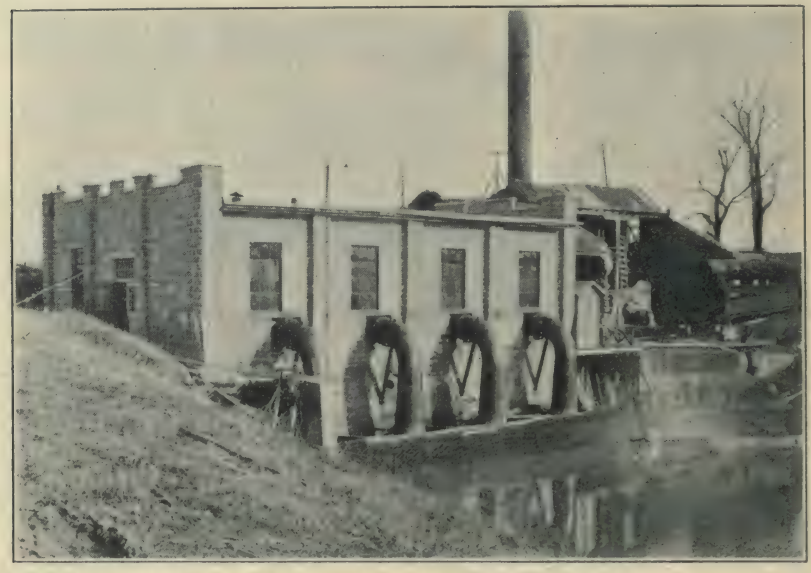


FIGURE 15.—McGee Creek drainage pumping plant, showing concrete block housing for oil engine units and brick structure over steam stand-by units

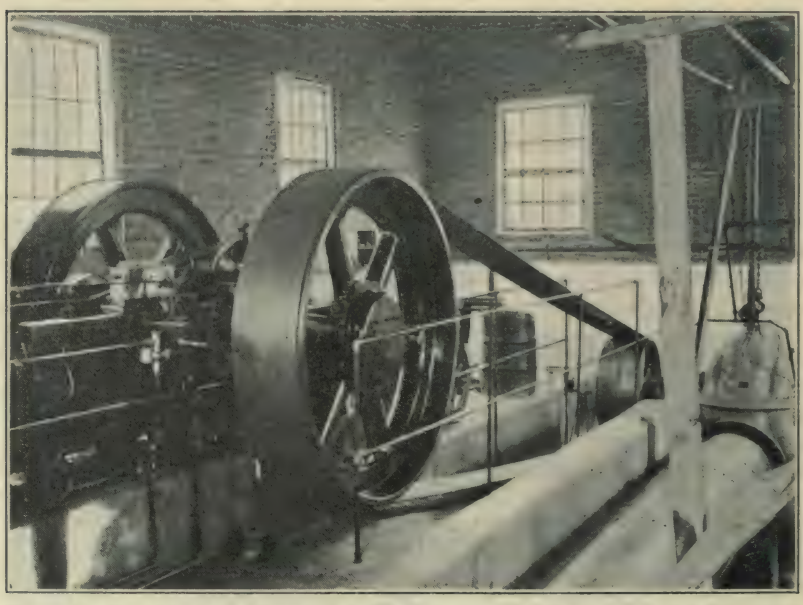


FIGURE 16.—Semi-Diesel 150 horsepower engine belt-connected to 30-inch pump, in Scott County drainage pumping plant

12 per cent plant factor, 1.5 cents at 19.1 per cent, and about 1.2 cents at 30 per cent plant factor. These low costs were influenced by the low cost of the building and foundations. (Fig. 15.) The cost per brake horsepower-hour for the Scott County plant (fig. 16) was

much higher at less than 30 per cent plant factor, although its engine and pump (unit No. 3) were identical with those (units Nos. 1 to 4) of the McGee Creek plants. Repair costs for both of these plants were negligible, because they pertain to new plants; it is certain that they will increase during later years. Fuel oil cost the McGee plant only 4.99 cents per gallon, because it was pumped directly into the storage tank from the railroad siding at the plant.

The cost per brake horsepower-hour was higher for the Eldred plant than for either the Scott County or the McGee Creek plant. The repair costs were larger because the large unit had been operated since 1921 and practically no repairs had been necessary before 1925.

For the Mauvaisterre plant, which had oil-engine equipment only, the average cost per brake horsepower-hour was 4.09 cents, at 10.8 per cent plant factor. This plant is operated very infrequently, because gravity drainage is obtained much of the time. For the Valley City plant the cost per brake horsepower-hour averaged 3.68 cents, at a plant factor of 10.2 per cent. This was principally due to the high fixed charges on the building. (Fig. 13.) Both the Mauvaisterre and the Valley City plants would have had much lower costs, probably approaching those for the electric group and for the oil-engine group using steam for stand-by equipment, had the plant factors been as great.

The average cost per brake horsepower-hour for the all-steam plants ranged from 2.25 cents for the Bay Island plant to 3.93 cents for the Henderson County plant. The former is exceedingly low. Its reasonableness is due to an average coal consumption of only 3.2 pounds per indicated horsepower-hour, to excellent maintenance of the plant by competent operators employed continuously since the plant began operating, and to low fixed charges. At the Henderson County plant the repair costs were excessive on account of the age of the equipment. The records for the Crane Creek plant are considered more typical of what may be expected of most of the steam pumping plants now operating. Its rate of coal consumption was 5 pounds per indicated horsepower-hour, which was less than that of the Henderson County plant. Its cost per brake horsepower-hour was 3.24 cents at a plant factor of 13.6 per cent, which is considerably greater than that for either the electric group or the oil-engine group at approximately equal plant factors.

COST PER ACRE-FOOT PUMPED

Cost per acre-foot varies not only with the plant factor but also with the lift pumped against and the over-all efficiency of the plant. The lift, however, does not affect the cost of pumping as much as many persons suppose. In an average plant using centrifugal pumps, to pump a given quantity at 10-foot lift requires approximately 70 per cent as much power as at 20-foot lift. Power required does not decrease in proportion to the static lift, because the pump efficiency decreases rapidly and the friction losses in pipes become larger, because of higher water velocities, at the lower lifts. It was found that for an electric plant the cost of pumping against a 10-foot lift is something like 80 per cent of the cost of pumping the same quantity of water against a lift of 20 feet. With a Diesel plant the total cost of pumping against a 10-foot lift would probably be 90 per cent of that of pumping against a 20-foot lift, because the fuel-oil cost is small.

The average cost of pumping for all the electric plants amounted to 77 cents per acre-foot, at 14 per cent plant factor, 9.45 feet lift, and 41.8 per cent over-all efficiency. This cost was highest at the Banner Special and Hartwell plants, as was the case for the cost per brake horsepower-hour. The low cost of 54 cents per acre-foot at the Henderson County plant was due to the low lift (6.67 feet) and the high over-all efficiency (36.6 per cent) for such a low lift. The other electric plants showed average costs per acre-foot ranging between 71 and 91 cents.

The average cost per acre-foot for the group of oil-engine plants using steam stand-by equipment was 69 cents per acre-foot, at a plant factor of 15.8 per cent and a static lift of 10.21 feet. The average over-all efficiency was characteristically lower than for the electric plants. The costs per acre-foot for the Eldred, McGee Creek, and Scott County plants did not differ greatly although there were considerable differences in plant factor, lift, and over-all efficiency.

For the steam stand-by units in the three districts above mentioned, the costs per acre-foot were high like the costs per brake horsepower-hour. For the Mauvaisterre and Valley City plants, using oil engines only, the cost per acre-foot averaged $1.02. The principal reason for this comparatively high cost was the high cost per brake horsepower-hour, which was due to low plant factor.

With the steam plants in regular service, the average cost of pumping per acre-foot was less than with any other group, averaging 55 cents at a plant factor of 18.3 per cent and a lift of 7.01 feet. This was due to the exceptionally low coal consumption of the Bay Island plant and to the high over-all efficiency of 45 per cent for the group. (Table 46.) The Bay Island plant had the lowest cost, 48 cents per acre-foot, and the Crane Creek plant, pumping against a considerably higher lift, had the highest average cost, 91 cents per acre-foot. For the Henderson County plant the average cost was only 57 cents per acre-foot, in spite of its high cost per brake horsepower-hour. This resulted from its high over-all efficiency of 49 per cent and low lift of 5.96 feet.

COST PER ACRE OF WATERSHED

The average cost per acre of watershed, Table 47, increases especially as the depth of run-off increases. As the run-off varies so greatly, the comparisons based on cost per acre of watershed are of more limited application than the unit costs based on work done or water pumped.

The average cost per acre of watershed for the electric plants was $1.40, for an average run-off pumped of 21.75 inches depth and a static lift of 9.45 feet. For the individual plants this cost ranged from $0.81 for the Indian Grave plant to $2.79 for the South Beardstown plant. The low cost for the former was due to pumping only 13.18 inches depth of run-off at a lift averaging only 4.74 feet. The high cost for the South Beardstown plant was due to pumping 40.48 inches depth of run-off at 15.35 feet average lift. For the other electric plants the costs were from $1.03 to $1.80 per acre.

The cost of pumping per acre of watershed for the oil-engine plants with steam stand-by equipment combines the costs with both types of power and amounts to $1.13 for a total run-off pumped of 17.28 inches at 10.21 feet lift. For the Eldred this cost was $1.77 per acre, the average run-off pumped being 20.9 inches and the lift 8.35 feet.

For the McGee Creek and the Scott County the average costs were 88 cents and 98 cents, respectively. These were considerably below that for any electric plant except the Indian Grave. However, the latter plant had a power rate lower than any available to other districts, and its average static lift was less than half that of either the Indian Grave or the McGee Creek plant. On the other hand, the McGee Creek plant has a total run-off capacity of 0.401 inch per 24 hours, affording much better drainage protection than the 0.273 capacity of the Indian Grave plant.

The average cost per acre of watershed for the two plants using oil engines only, 90 cents per acre, was lower than that of any other group. However, the run-off pumped was only 10.54 inches, and the static lift was 9.31 feet. Had these plants operated under the same conditions as the oil-engine plants using steam stand-by equipment, the cost per acre drained would have been about the same.

For the three steam plants the average annual cost per acre of watershed was $1.06, which probably is less than the average for all steam plants operating in the upper Mississippi Valley. The static lift for the group was less, and the run-off depth was greater than for any other group. The cost for the Bay Island plant was less than that for any other steam plant, on account of its run-off capacity of only 0.234 inch per 24 hours and its high over-all efficiency of 40 per cent. The high cost, $1.68 per acre, for the Henderson County plant was largely due to the high run-off pumped.

COST PER ACRE ASSESSED

The cost per acre assessed is nearly always greater than the cost per acre of watershed, because certain lands in the districts such as highways, ditches, and levee rights of way and areas outside the districts are drained by the pumping plant but can not be assessed for benefits.

The average cost per acre assessed for the electric plants was $1.84. The average for the oil-engine plants with steam stand-by units was $1.48 per acre assessed, and that for the plants having only oil engine pumping units was $1.46. For the all-steam plants this cost was $1.96 per acre. The great difference between this and the cost per acre assessed is due to some 28,400 acres drained to the Bay Island plant from outside the district. Diversion of much of this outside drainage by a channel under construction will greatly reduce this cost.

RELATION OF COST OF PUMPING TO RUN-OFF DEPTH

The run-off pumped from most districts includes both surface run-off and seepage. The seepage comes from the hill lands or the river, largely through strata of sand or gravel. It is especially great in districts where drains touch sand strata for long distances. The amount increases as the river rises, the increase being especially rapid when the river is above the level of the land.

The differences between the districts in cost of pumping per acre of watershed are due largely to differences in the depth of run-off pumped. This factor has greater effect than any other upon this unit cost. Table 48 lists the plants in order of depth of run-off pumped, and shows that in general the cost per acre drained increases as the depth of run-off increases.

TABLE 48.—*Cost per acre of watershed and depth of run-off pumped*

Plant	Power type	Length of record	Average annual rainfall	Average run-off pumped per year	Average static lift	Annual cost		Average overall efficiency
						Per acre of watershed	Per brake horsepower-hours	
		Years	*Inches*	*Inches*	*Feet*	*Dollars*	*Cents*	*Per cent*
Mauvaisterre	Diesel	2.73	41.29	7.43	6.10	0.65	4.09	25
Banner Special	Electric	1	27.61	8.98	10.38	1.03	5.42	50
Fabius	Diesel	4	39.71	10.24	4.83	1.11	6.16	22
Indian Grave	Electric	5	34.23	13.18	4.74	.81	2.57	21
Valley City	Semi-Diesel	3.87	34.48	13.64	11.07	1.15	3.68	43
Hartwell	Electric	2	35.80	13.75	11.65	1.33	3.99	51
Scott County	Semi-Diesel and steam	2	31.57	13.81	[1] 13.65	.98	[1] 1.90	[1] 37
McGee Creek	do	3	35.71	13.87	[1] 9.63	.88	[1] 2.11	[1] 29
Hunt	Electric	2.70	37.17	16.29	8.53	1.24	2.49	41
Bay Island	Steam	6	38.94	18.21	7.17	.74	2.25	40
Crane Creek	do	5.89	39.53	20.38	12.44	1.55	3.24	54
Green Bay	Electric	1	38.31	21.65	10.67	1.47	2.88	48
Coal Creek	do	16	35.11	23.94	12.14	1.80	2.42	40
Eldred	Diesel and steam	6	38.30	24.15	[1] 8.35	1.77	[1] 2.47	[1] 33
Lima Lake	Electric	2	34.10	26.56	9.83	1.57	2.43	42
Henderson County	do	2.63	40.24	30.95	6.67	1.40	2.41	37
Do	Steam	2.20	39.67	35.64	5.96	1.68	3.93	49
South Beardstown	Electric	6	37.85	40.48	15.35	2.79	2.38	54

[1] For oil-engine units only.

The data for the three plants that pumped less than 11 inches of run-off, for $0.65 to $1.11 per acre of watershed, are believed to be representative for districts that obtain considerable gravity drainage or for years of subnormal precipitation and low river floods. However, the average cost for the Fabius plant is excessive on account of extraordinary repairs charged to operating expenses.

Five plants pumped average annual run-off depths of between 13 and 14 inches, at costs ranging from $0.81 to $1.33 per acre of watershed. These figures are considered representative of average conditions for districts in the upper Mississippi Valley that pump all their drainage but are elevated enough not to be affected by seepage to any large degree.

For two plants that pumped between 16 and 19 inches of run-off per year the costs were $0.74 and $1.24 per acre of watershed. One of these was the very economical and efficient Bay Island plant.

Average annual run-off depths between 20 and 25 inches were pumped by four plants, at average costs of $1.47 to $1.80 per acre of watershed. The average annual run-off pumped by the Green Bay plant from 1919 to 1930, estimated from pump ratings and the record of current used, was 10 inches greater than the figure shown in Table 48. These plants undoubtedly handled appreciable amounts of seepage, but the Coal Creek and Crane Creek plants must have pumped less than would need to be pumped by most plants having as great static lifts.

Four plants pumped 26 to 40 inches depth of run-off per year at average costs ranging from $1.40 to $2.79 per acre of watershed. The Henderson County and South Beardstown districts are affected by backwater from dams, pump against constant lifts, and have very sandy subsoils. Consequently they have to pump very large amounts of seepage.

BACKWATER FROM DAMS

The data collected seem to show that in a number of instances backwater from dams in the rivers has increased the cost of pumping by increasing the amounts of seepage into the districts. This condition is shown in Table 49, where two districts affected by backwater from the dam at Keokuk, Iowa, and three districts affected by the dam at La Grange, Ill., are compared with three Mississippi River districts not affected by backwater. The average rainfall for the three groups is so nearly the same that differences in the run-off appear to be due almost entirely to differences in seepage caused by the backwater from the dams.

TABLE 49.—*Effect of backwater from dams on average annual amount of pumping and cost of pumping per acre of watershed*

District	Period of record	Average annual rainfall	Average annual run-off depth pumped	Average static lift	Increase in low-water lift caused by dams	Average annual cost per acre of watershed
		Inches	*Inches*	*Feet*	*Feet*	*Dollars*
GROUP 1. DISTRICTS NOT AFFECTED BY DAMS (MISSISSIPPI RIVER)						
Bay Island	1925–1930	38.94	18.21	7.17	0	0.74
Indian Grave	[1] 1925–1930	34.23	13.18	4.74	0	.81
Fabius	1925–1928	39.71	10.24	4.83	0	1.11
Average		37.63	13.88	6.16		.82
GROUP 2. DISTRICTS AFFECTED BY KEOKUK DAM (MISSISSIPPI RIVER)						
Green Bay [2]	1919–1930	36	32	10.5	10	1.60
Henderson County	1926–1930	39.98	33.09	6.32	6	1.53
Average		37.99	32.55	7.90	8	1.56
GROUP 3. DISTRICTS AFFECTED BY LA GRANGE DAM (ILLINOIS RIVER)						
Coal Creek	[3] 1914–1930	35.11	23.94	12.14	10	1.80
Crane Creek	1925–1930	39.53	20.38	12.44	10	1.55
South Beardstown	1925–1930	37.85	40.48	15.35	10	2.79
Average		37.50	28.27	13.88	10	2.10

[1] Year 1929 not included.
[2] The amount of water pumped by the Green Bay plant was computed from the records of electric-current consumption, 1919 to 1930, and plant tests in 1925; average costs were computed from actual cost records for the same period. The pumps operated at constant speed and against nearly constant lift.
[3] Year 1922 not included.

The three districts not affected by backwater (group 1 in Table 49) need to do but little pumping during low stages of the river, because the water level inside the district does not vary greatly from the stage of the river. The average depth of run-off pumped per year by these three districts has been 13.88 inches. The records for the Fabius district, which obtains gravity drainage, are representative of conditions obtaining at several districts along the Mississippi.

For the two districts affected by backwater from the Keokuk Dam (group 2), the depth of water pumped per year averaged 32.55 inches, or more than twice that for the districts not affected by backwater. Also, the average lift was greater than that for the districts not affected by backwater. The dam has raised the low-water stage about 10 feet

at the Green Bay plant and 6 feet at the Henderson County plant. Seepage into these districts is continuous, and the pumps must be operated steadily even during dry weather. The average depth pumped by the Henderson County plant was greater than that pumped by the Green Bay plant, even though the average lift was less. Seepage into the Henderson County district is believed to have been greater, because of unusual subsoil conditions, than that into most districts having equal static lifts. The records for the Green Bay district are considered more generally representative of the effect of backwater from dams on the amount of drainage pumping.

In the three Illinois River districts (group 3), the dam at La Grange has raised the low river stage approximately 10 feet. The average depth of water pumped from these districts ranged from 20.38 to 40.48 inches, but the average, 28.27 inches, is considerably less than that for the two districts affected by backwater from the Keokuk Dam. Seepage into the South Beardstown district was very great because that district is low in relation to the river, and like the Henderson County district, has a very sandy subsoil.

The average annual cost of pumping by group-1 plants, which are not affected by backwater, was only 82 cents per acre of watershed, whereas that for group-2 plants, affected by backwater from the Keokuk Dam, was $1.56 per acre and that for group-3 plants, affected by backwater from the La Grange Dam, was $2.10 per acre. These costs are in the ratio of 1:1.9:2.5.

Backwater from a dam may cut off the flow from a district that naturally has a free gravity outlet and ordinarily would not have to pump for drainage during low stages of the river. In the case of the Henderson County and the Crane Creek districts there is little doubt that considerable gravity drainage could be obtained were it not for the backwater from the dams. Prior to the time the dam was put in, a large part of the Crane Creek district was cultivated without pumping. In addition to increasing the amount of pumping, backwater from dams no doubt has caused a permanent rise in the groundwater table in affected districts, making impracticable the cultivation of certain areas which otherwise could be cultivated, and has necessitated the installation of additional drains for yet other cultivated lands.

APPLICATION OF DATA

Great care must be exercised in applying the data contained in this report to other districts, because so many factors affect the cost of pumping. Determination of the probable run-off and of the maximum, minimum, and average static lifts are of primary importance in selecting pumping equipment, but discussion of the design and operation of plants is not within the scope of this bulletin. Comparison of the costs of pumping with oil engine and with electric power under the same conditions is probably the most general application of the data at the present time. The following examples of such use for assumed conditions indicate the trend in the relation of the costs with these power types:

EXAMPLE 1

For a watershed area of 18,600 acres, a maximum plant capacity of only 0.2 inch per 24 hours, an average run-off depth of 10 inches per year, and an average lift of 4 feet there would be required a

pump capacity of 70,000 gallons per minute and a motor or engine capacity of 500 horsepower. The estimated costs for plants of these capacities in 1930, based on actual competitive bids, are $80,000 for the oil-engine plant and $60,000 for the electric plant.

Fixed charges have averaged approximately 9 per cent for oil-engine plants and 8 per cent for the electric plants. These percentages applied to the costs used in this example give $7,200 per year for the oil-engine plant and $4,800 per year for the electric installation. The labor costs are estimated as $1,800 and $1,200 per year for the respective power types. Observation has indicated the economy of employing competent operators for all drainage pumping plants.

The consumption of fuel by oil-engine plants is estimated as 0.075 gallon per brake horsepower-hour, including waste, and the power consumption as 16 brake horsepower-hours per acre-foot at 4-foot lift, which can be readily obtained in modern Diesel plants. The cost of fuel oil is estimated at 6 cents per gallon delivered to the plant, making the total $1,116 per year. The average cost of current for the electric plant was determined according to the off-peak rate (p. 21) now used by the Coal Creek and other plants, which is ordinarily the cheapest rate now available for drainage districts. The actual costs per kilowatt-hour for the plants using this rate were plotted against plant factor, and an average curve drawn. Electric rates in these examples were determined from this average curve. It has been found economical to design more efficiently for electric plants than for oil-engine plants because a reduction in current used effects a larger money saving than a proportionate reduction in fuel oil. Such differences in efficiency usually occur through improved and more costly pipe designs. For this reason a lower consumption of 14 brake horsepower-hours per acre-foot at 4-foot lift was estimated for the electric plant. On this basis, average cost per kilowatt-hour is determined as 2.07 cents for a plant factor of 5 per cent, and the average cost of current as $4,806 per year.

Lubricating oil is a considerable item with an oil-engine plant, and its cost is estimated as one-fifth that of fuel oil, or $223. This ratio obtained approximately in the most typical group of oil-engine plants studied. The cost of repairs and supplies, miscellaneous, and overhead for this plant was estimated as 15.04 per cent of the total for fixed charges, fuel oil, and labor, and the same cost for the electric plant, including lubricants, as 7.64 per cent. These ratios are based on the group averages shown in Table 47. (Cost figures for the oil-engine plants having stand-by equipment were used, because considered more representative.)

The total annual costs of pumping thus are estimated as $11,860 with the oil-engine plant and $11,632 with the electric plant, indicating a difference of $228 per year in favor of the electric plant.

For a static lift of 8 feet instead of 4 feet, the costs of pumping were estimated in the same manner as just described except that $100 additional labor expense was estimated for each plant, and it appeared that there would be a difference of $345 per year in favor of the oil-engine plant. For a run-off depth of 20 inches instead of 10 inches per year, similar computation showed that pumping with the oil-engine plant would be cheaper by $956 per year at 4-foot lift, and by $1,928 at 8-foot lift, than pumping with the electric plant.

EXAMPLE 2

For the watershed area used in example 1, a plant with capacity to pump 0.3 inch per 24 hours would require a 750-horsepower oil engine or motor. Such a plant would cost about $115,000 with oil-engine or $85,000 with electric equipment. Costs of pumping computed by the method used in the preceding example indicate that for 10 inches run-off and an average lift of 4 feet, pumping with the electric plant would be cheaper by $1,056 per year than with the oil-engine plant, while for 10 inches run-off and 8 feet average lift the electric plant would be cheaper by $211 per year. For an average run-off of 20 inches, pumping with the oil-engine plant apparently would be cheaper by $615 per year at 4 feet average lift, and by $1,624 per year at 8 feet average lift, than pumping with the electric plant.

EXAMPLE 3

For a watershed area of 12,400 acres, a plant to pump 0.3 inch depth of run-off in 24 hours would be like that required in example 1. Computations made as before indicate that the total cost of pumping would be less with the oil engine than with the electric plant, by $431 per year for pumping 20 inches annual run-off against 6 feet average lift, by $1,378 per year for 20 inches run-off against 12 feet lift, by $1,226 per year for 30 inches run-off against 6 feet lift, and by $2,732 per year for pumping 30 inches annual run-off against 12 feet average lift.

The foregoing examples show the effects of variations in quantity of water pumped and in lift upon the cost of pumping with an oil engine and with electric power, rather than under what conditions either one or the other type of power will be more economical. Changes in power rates, which have been downward since about 1920, or in the estimated life of oil engines for drainage pumping, which so far has had to be based upon somewhat limited experience, might affect materially such comparative estimates as those given.

For any proposed installation it is very important to determine operating conditions carefully and to estimate costs accurately. Alternate bids on oil engine and electric equipment are desirable to determine first costs accurately. For a plant of large capacity that will be required to do relatively little pumping, electric equipment will have the advantage because of its lower first cost. Where large amounts of pumping will be required in proportion to plant capacity, the oil-engine equipment generally will be more economical because the operating costs, exclusive of fixed charges, do not increase nearly as rapidly with increase in the amount of pumping for the oil-engine plant as for the electric plant.

FACTORS AFFECTING CHOICE OF POWER TYPE

A comparison of electric and oil-engine power for drainage pumping should deal with other factors besides cost as discussed on preceding pages. Electric power has been more reliable than oil-engine power, especially in plants that contained not over two units. Although motors sometimes have burned out during emergencies, interruptions in electric-pumping service have seldom or never exceeded a few hours duration because power companies have been instrumental in obtaining motors for temporary use while repairs were being made. On the

other hand, at least two districts have suffered considerable damage through failure of one or both of their oil engines to operate during flood periods; but it must be noted that one of the plants was about 11 years old and had received very poor care, and the other plant was 7 years old, had been poorly cared for, and was overloaded at the time of the breakdown. Oil engines that were large enough to operate continuously and with some power in reserve, that were maintained in good operating condition, and that have received proper care while operating, have rendered satisfactory drainage service.

The Diesel or semi-Diesel plant requires a more skilled operator than the electric plant, and competent men are more difficult to obtain. The oil-engine plant usually requires much closer and more careful supervision than the electric plant, particularly in the purchase of fuel and lubricating oils and in obtaining repairs to the engine when needed. Unfortunately, there has been a tendency in many districts to delay making necessary repairs so long that excessive damage to the equipment has resulted.

The life of oil-engine equipment is more uncertain and more likely to be shortened by improper installation or operation than that of an electric motor. A few oil engines in drainage pumping plants have operated less than 10 years, because of poor foundations, improper transmission equipment, or improper operation. Oil engines are believed to be dependable when the standard product of a reliable manufacturer is properly installed and operated. Some of the unsatisfactory oil engines have been more or less experimental, but the vertical multiple-cylinder and the horizontal single-cylinder types of both Diesel and semi-Diesel engines, operated between 200 and 260 revolutions per minute usually have given satisfactory service. Higher speed engines are coming into favor, but so far none has been installed for drainage in this region.

The electric plant is the easier to start and stop, which is of considerable advantage in maintaining a constant stage of water in the district. However, when such a plant is operated during off-peak hours to obtain a cheaper rate for current, part of the flexibility of the electric plant is lost. Considerable labor on the part of the operator is required to start an oil-engine plant, but very little additional fuel is required in making frequent starts and stops.

The steam plant is the least flexible of the three types. On account of the large fuel losses incident to firing up and closing down the plant, the starting of the pumps always is delayed as long as possible. As a result the drainage of a district using that type of power sometimes suffers. During recent years many old steam plants have been abandoned because of high costs of labor, coal, and repairs, and sometimes because of poor mechanical condition which made plant operation uncertain. However, it is not economical to abandon a steam plant that is dependable and economical of operation. Though some other power type may appear cheaper, the additional fixed charges for the new machinery usually will exceed the saving in operating expenses if the steam equipment is in good condition. When the old equipment fails to furnish satisfactory drainage protection, or when the coal consumption exceeds 6 pounds per indicated horsepower-hour, it probably will be economical to install electric or oil-engine units to do most or all of the pumping.

SUMMARY AND CONCLUSIONS

A careful study extending over a period of six years has been made of 17 drainage pumping plants in the upper Mississippi Valley, and a total of 70 plant-years of records have been compared. Daily records of operation were kept at the plants to determine accurately the rainfall, quantity of pumping, static lift, and plant efficiencies, these being the principal operating factors affecting the cost of pumping. There was considerable variation in the elevations of the districts in relation to the river, and consequently the static lifts and the depths of run-off varied greatly. The minimum lifts for the districts ranged from 0 to 8 feet, while at flood stages the maximum lifts usually varied from 12 to 25 feet. Average lifts for the districts studied varied from 4.74 feet to 15.35 feet. These are considered representative of general conditions in the region.

The districts having no gravity drainage pumped an average yearly run-off of 13 to 40 inches depth over the watershed area. This great difference in run-off was largely due to difference in the amounts of seepage, because the average rainfall was approximately the same. Seepage comes from rivers or near-by hill lands. It increases as the static lift increases and is especially great when the river rises above the level of the land.

Several districts were affected by backwater from dams to such an extent that the river level was from 6 to 8 feet above the level of the water in the districts at normal low-water stage. It was found that such districts pumped almost double the quantity of water pumped by similar districts not affected by dams.

Many of the plants studied operated at comparatively low pump efficiencies. This was partly due to poor design and partly to improper operation. The more recently constructed plants have, as a rule, been more efficient, because of more widespread knowledge and understanding of the operating conditions on the part of engineers designing plants and on the part of machinery companies supplying equipment. This study of the costs has emphasized the importance of securing properly qualified persons to design, construct, and operate such plants.

Three types of power have been used in recent years to operate drainage pumping plants—steam, electric, and oil engine. Steam was the earliest type used, but no new steam plants have been built since 1920. Much of the old steam equipment has been replaced by electric or oil-engine units because it was not dependable and was too expensive in operation. The expediency of substituting more economical equipment should be carefully considered for plants where the coal consumption exceeds 6 pounds per indicated horsepower hour.

Under conditions obtaining at the time these studies were concluded electric and oil-engine power are the most economical types to use. At about 15 per cent plant factor the average total cost of pumping by the oil-engine group of plants was 2.2 cents per brake horsepower-hour, and by the electric plants 2.7 cents. At slightly higher plant factor the average cost for the steam group was 2.9 cents per brake horsepower-hour. Below about 12 per cent plant factor the cost of pumping with the electric plants generally was less than with the oil-engine plants, and above 12 per cent plant factor generally was more. However, the point of equal cost for the two power types is by no

means established, for omission of any one of the plants in the oil-engine group would have changed the result appreciably.

The average costs per acre-foot pumped were $0.69 for the oil-engine group and $0.77 for the electric group, at approximately 10-foot average lift and only slightly different plant factors. The cost for the steam plants was only $0.55 per acre-foot at a static lift of about 7 feet, but as previously indicated this is much less than could be obtained with similar plants built at prices current during the past decade.

The average annual costs per acre of watershed were $1.13 for the oil-engine group, including the costs of the steam stand-by units, and $1.40 per acre for the electric plants. Part of this difference was due, however, to the difference in the amounts of run-off pumped, which were 15.07 inches by the oil-engine group and 21.75 inches by the electric group. Had the former plants pumped as great a run-off per acre as the other, the average cost would have been increased to probably something like $1.25 per acre. For the all-steam group, pumping 24.74 inches of run-off, the cost per acre of watershed was only $1.06, reflecting the low cost per acre-foot pumped.

The average annual costs per acre assessed, for the plants studied, were $1.84 for the electric group, $1.48 for the oil engine group, and $1.96 for the steam group. This cost bears no definite relation to any other unit cost except that it is larger than the cost per acre of watershed.

Cost per brake horsepower-hour is the most accurate basis of comparing different types of proposed drainage pumping installations, but requires careful investigation and sometimes considerable time and expense for determining the plant capacity and plant factor. The cost per acre of watershed is more convenient, especially for preliminary estimates covering new pumping enterprises, but is subject to considerable uncertainty in the assumption that must be made regarding depth of run-off to be pumped.

Fixed charges constituted 45 per cent of the total cost of pumping with oil engine and 33 per cent with electric power. This fact emphasizes the greater importance of economy in first cost for oil-engine plants than for electric plants, but perhaps undue effort to economize in this particular has been the cause of unsatisfactory service, high cost of repairs, and short life of some oil-engine installations.

Fuel and lubricants have constituted 23 per cent of the cost of pumping with the oil engine plants, while current has constituted 53 per cent with the electric plants. This comparison emphasized the special importance in the latter type of an advantageous power rate and of efficiency in both design and operation of the whole plant.

The difference in labor costs, which were 19 per cent for oil-engine plants and 7 per cent for electric plants, are largely inherent in the types of equipment. The same is true concerning difference in costs for repairs and supplies, which were 6 per cent and 2 per cent for the respective power types. The miscellaneous and overhead expenses amounted to 7 per cent for the oil-engine plants and 5 per cent for the electric plants.

General and local conditions affecting prices of materials, labor, and equipment should be considered when applying the data presented herein to any particular situation. When a new plant is to be built, or when existing pumping equipment is to be replaced or supple-

mented, selection of the type of power should be made only on the basis of competitive bids for the equipment and careful analysis of the conditions of operation, as is illustrated by the examples that have been given on pages 94–96. With the relative costs of the different kinds of equipment there should be considered also the relative convenience and dependability under the particular circumstances of the proposed installation.

○

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Division of Drainage and Soil Erosion Control.	L. A. JONES, *Chief.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

TECHNICAL BULLETIN No. 326 OCTOBER, 1932

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

BREEDING THE HONEYBEE UNDER CONTROLLED CONDITIONS

By W. J. NOLAN, *Apiculturist, Division of Bee Culture, Bureau of Entomology*

CONTENTS

	Page
Introduction	1
Status of work on breeding under controlled conditions	4
With natural insemination	4
With artificial insemination	5
Breeding work at the bee culture laboratory	11
Results of artificial insemination	12
On queens used in 1927, 1928, and 1929	12
On queens used in 1930	13
On queens used in 1931 and 1932	17
New instruments and methods for artificial insemination	21
Glass holder	21
Mount for glass holder	22
Spreading and holding abdominal tips	23
Multiple set-up	27
False stage	28
Pipette manipulator	28
Pipette	30
Use of an anesthetic	30
Filling the pipette	31
New instruments and methods for artificial insemination—Continued.	
Mucus plug	31
Marking individuals	33
Drones	34
Obtaining drones	34
Determining sexual maturity of drones	35
Queen rearing and testing	36
Experiments in 1930	36
Apartment hives	37
Wintering in apartment hives	40
Queen rearing in 1931	41
Hive records	42
Viability of spermatozoa	42
Successive inseminations	43
Mixing sperm from different drones	44
Optimum age of queen for artificial insemination	44
Succession of generations	45
Summary	46
Literature cited	47

INTRODUCTION

Although the honeybee has been kept by man since long before the Christian era, yet in the course of the centuries little or no change has been wrought in it by breeding if the development of the so-called "golden" strain of Italians in the United States and of the "veredelte" strains of the German brown race in central Europe is excepted. The fact that in nature the honeybee mates only on the wing is commonly given as the principal reason for this situation.

Even t[illegible] bee breeders have relied on natural matings in their work with the honeybee during the centuries, they would have made progress more comparable with that accomplished in the breeding of man's other useful animals had it not been for two factors. In the first place, even less than 100 years ago the bee breeder did not have adequate knowledge of reproduction in the honeybee since he did not know how drones develop. In the second place, until recently he had devised no means of distinguishing definitely between races of the honeybees and their various strains. Even Mendel (Iltis, *19, p. 142–157*)[1], the father of modern genetics, lacked such means when he endeavored to work out problems of bee genetics in addition to those on peas which brought him fame.

[1] Italic numbers in parentheses refer to Literature Cited, p. 47.

It is unfortunate that Mendel's detailed records have never been brought to light. His studies were not confined to one race of the honeybee, since it is reported (*19*) that he worked on the heather or Dutch bee, the Italian, the Carniolan, the Egyptian, and the Cyprian, in addition to the native bee of his region. He used colonies kept under natural apiary conditions in his cloister garden at Brno. (Fig. 1.)

Modern scientific information on reproduction in the honeybee had its beginning in 1669, when Swammerdam (*46, pt. 1, p. 159*) described clearly the egg-laying function of the queen. The question of the place of mating remained unanswered until over a

FIGURE 1.—Mendel's apiary in his cloister garden in Brno, Czechoslovakia. (Iltis) (Published with permission of Julius Springer, Berlin)

hundred years later, when Huber (*18, p. 34*) established the fact that the queen bee mates outside when in flight. This problem had baffled even so keen an observer as Réaumur, whose interest in it (*44, v. 5, p. 502*) led him to attempt to have a queen and drone mate in a glass dish on a table. Huber also tried the same experiment before reaching his final solution. Another important advance had taken place shortly before Huber's discovery, when Schirach, according to Christ (*7, p. 9*), showed definitely that a queen can be reared from any worker larva if it is given proper food and care early enough in its larval life. Not until 1845, however, was Dzierzon's amazing discovery made public (*12, p. 107*) that the drone is produced parthenogenetically. Little progress could be expected of the bee breeder without at least knowledge of these four fundamental truths.

It is only since 1900 that a way has been opened to the bee breeder for distinguishing accurately between various races and strains of

the honeybee, as a result of studies undertaken to determine, especially from the standpoint of biometrics, characteristics marking them. The pioneer in this type of bee research was Koshevnikov, of Russia. Among others who have made contributions in this field are Alpatov and Mikhailoff, also of Russia; von Buttel-Reepen, Zander, and Götze, of Germany; Rytiř, of Czechoslovakia; Tokuda, of Japan; and Phillips and Kellogg, of the United States.

Within the past decade another tool has been placed in the hands of the bee breeder with the establishment of the fact that queen bees can be inseminated artificially. This makes possible full control with regard to the drones used in breeding. It is true that artificial insemination of the honeybee is, as yet, only an instrument of the scientific investigator and that the commercial breeder must continue, for a time at least, to rely on natural inseminations for his work. The way has been opened, nevertheless, for the investigator in any locality to keep pure stock of various races and strains as well as to develop special strains of the honeybee. The commercial breeder can thus, in turn, be provided with a continuous reserve from which to replenish his stock if natural matings fail him.

Many problems await the bee breeder. He might develop strains which would be gentle, disease-resistant, capable of carrying larger honey loads, capable of flying longer distances, or which would have tongues of the proper length to secure nectar from floral sources not now available to the honeybee. For some regions it would seem desirable to develop strains that fly at lower temperatures than do bees now commonly found in the United States. This is of particular importance to those interested in bees as pollenizing agents.

In general, breeding of the honeybee in modern beekeeping practice falls under two main headings: (1) Breeding under natural or uncontrolled conditions, and (2) breeding under artificial or controlled conditions. By natural or uncontrolled conditions are meant those obtaining in nature or ordinarily in the apiary, where virgin queens and drones fly freely and mating takes place only on the wing. By artificial or controlled conditions are meant both those which, while permitting natural insemination to occur, obtain through some restriction by the beekeeper as to the particular drone or drones with which the queen may mate, the flight range of the queen, or the flight range of both queen and drones, and those which obtain when the beekeeper causes the transfer of spermatozoa from drone to queen to be made otherwise than as in nature.

The following outline, in connection with the text which immediately follows, may prove helpful in keeping clear the distinction between the various methods which are in use or have been tried for breeding the honeybee:

BREEDING OF THE HONEYBEE

1. Uncontrolled conditions (little or no restrictions on queen or drones; mating on the wing).
2. Controlled conditions.
   - A. Natural insemination.
     1. Available drones restricted (mating stations).
     2. Flight range of queen restricted (tethering, etc.).
     3. Flight ranges of both queen and drones restricted (tents, greenhouses).

Controlled conditions—Continued.
B. Artificial insemination.
1. By placing drone organs in position in queen.
a. Before separation from drone.
b. After separation from drone.
2. By removing sperm from drone organs first.
a. External application (brush, squeezing out sperm, etc.).
b. Internal application (injecting within genital opening).

It is to be noted that this outline does not include such methods as daubing the eggs with sperm, since this is an attempt to accomplish fertilization of the egg itself and not to simulate mating of the queen bee.

STATUS OF WORK ON BREEDING UNDER CONTROLLED CONDITIONS

WITH NATURAL INSEMINATION

The mating stations of Europe furnish a practical example of controlled conditions which restrict the drones with which the queen may mate, but which still permit a natural insemination to take place. These stations are in isolated localities in which the beekeeper has endeavored to have only drones of his own choice present. The virgin queen is taken there and is free to fly from her nucleus and to mate on the wing with these drones. The breeding experiments conducted a number of years ago in Texas by Newell (*29*), as well as those in progress on an island in Lake Ontario by Sladen, of Canada, at the time of his death in 1921, also come under this category.

Many good results are reported from the breeding work carried on at these stations in Europe, especially in Switzerland. The work in Switzerland is linked with the name of Kramer (Goldi, *14*), who started the movement in his country to maintain in purity and to improve the native Swiss bee by having selected stock mate in isolated localities. (Fig. 2.) The results of this work from 1915 to 1928, according to a survey of certain apiaries in Switzerland which contained colonies both of the improved (veredelte) and of unimproved stock (*21, p. 30*), show that the honey crop of the improved stock averaged higher per colony each year than that of the unimproved stock, ranging from 20 per cent in 1923 to 100 per cent more in 1924. These percentages, however, were based on the relation of the average per-colony yield for improved and unimproved stocks, respectively, to the sum total of the two averages, and the number of improved colonies used in the survey was larger each year than the number of unimproved colonies, being in 1928 about two and one-half times and in 1924 more than seven times as large.

In the United States isolated locations free from wild swarms or colonies of neighboring beekeepers are not easily accessible to most queen breeders. Consequently the mating station has played little or no part in beekeeping here, although certain commercial queen breeders in this country have attempted to duplicate, in a degree, conditions found in an ideal mating station by endeavoring to rid the territory in the immediate vicinity of their mating yards of undesirable colonies of bees. Their methods have consisted of buying up colonies found in the neighborhood, requeening near-by colonies with desired stock free of charge, paying rewards for wild swarms, and similar measures. The possibility that the queen may

mate with a stray drone even in a locality thought to be well isolated from local bees reduces somewhat the value of mating stations in a scientific breeding program.

Attempts to mate queens tethered at the end of a pole are examples of a partial restriction of the flight range of the queen bee, while attempts to have a queen and chosen drones mate inside a tent or other inclosure are examples illustrating both a restriction of the drones available for mating and a partial restriction of the flight range of queen and drones. In all these cases, however, there is an endeavor to have mating take place on the wing—in other words, to effect a natural insemination. Mendel was one of many who

FIGURE 2.—Mating station at Bruggen bei St. Gallen, Switzerland. (Kramer) (Published by permission of Verein Deutsch-Schweizerischer Bienenfreunde)

have unsuccessfully attempted to obtain matings of queen bees within inclosures (*19, p. 147*). This phase of controlled mating was also investigated in the Bureau of Entomology in 1907 (*17*). Since no satisfactorily verified reports of success are available for matings attempted under the conditions given in this paragraph, no further attention will be paid this category at the present time.

WITH ARTIFICIAL INSEMINATION

When conditions are so controlled that both queen and drone are deprived of flight, the insemination must be accomplished artificially. This may be effected either by placing the drone organs in proper position in the queen to accomplish insemination or by removing the sperm from the drone organs and transferring it to the queen.

The methods proposed for bringing the drone's organs into proper position within the queen can be divided into two classes: (1) Causing these organs to evert in the proper position in relation to the

queen and then severing them from the drone, and (2) separating them from the drone and then placing them in proper position in the queen. The methods for first removing sperm from the drone and then transferring it to the queen can also be divided into two classes: (1) Dropping or brushing the sperm on or near the exterior genital opening of the queen, and (2) introducing the sperm within the opening.

One of the early attempts at the artificial insemination of queen bees, and one which is often quoted, was that by Huber, who followed the suggestion of Bonnet in 1789 that he endeavor to inseminate a queen bee by introducing within her vagina, through the use of a brush, sperm from a drone. Huber (*18*, *v. 1*, *p. 60*) failed in such an attempt, as have doubtless most of his successors, regardless of the method employed.

According to his statements before the Wanderversammlung der Imker deutscher Zunge, held in Leitmeritz in 1927, Wankler, of Germany (*48*), was one of the earliest modern queen breeders to attempt to make use of instruments in the insemination of queen bees. He affirmed that as early as 1885 he had resorted with some success to mechanical means for inseminating queen bees. He also referred to success attained by himself, even in the eighties, in fertilizing drone eggs from drone cells by daubing them with sperm.

Wankler (*48*) mentioned, among his instruments, a pipette (Spritze) to which could be attached a model (künstliche Glied) of the drone organs, a means for moving the pipette, and a block on which to hold the queen. He stated that the semen is forced into the pipette and then the model is attached and introduced into the vagina of the queen, which is bound to the block. The sperm is next forced out of the pipette into the model through pressure on a screw knob. The pipette, having served its function, is detached, but the model remains attached to the queen at least long enough for the semen to be taken up by the spermatheca. The queen is put back on a frame of brood under a cage of wire screening (Pfeifendeckel) fine enough to catch the model when it finally becomes detached from the queen and drops off.

It is to be noted that the talk by Wankler was given after Watson's announcement of his discovery and Wankler referred to it. Armbruster, however, in a preface to Wankler's book (*47*, *p. 5*) written in 1924, mentioned that Wankler had presented him with one of the pipettes made of silver and with a model of a drone organ fashioned in metal.

McLain (*22*) claimed that he had achieved success in 1886 in artificially inseminating queen bees with an instrument consisting of a fine nozzle fitted to a hypodermic syringe in place of the regular injecting needle. After the nozzle had been filled with sperm from the drone, a small tube was slipped over it. The queen was held in a clamp made of the two halves of a block of wood 2 inches square and 4 inches long in which a hole had been hollowed out to hold her body with the exception of the tip of the abdomen. McLain also reported success in having queen bees mate in a greenhouse, and even in squeezing sperm from a drone directly into the vestibule of a queen bee.

No other nineteenth-century attempts to inseminate queen bees artificially need be discussed here, since in no instance were such attempts repeated successfully by others to the conviction of the beekeeping world.

The first announcement of importance in this field in the twentieth century was that of Jager and Howard (*20*) in 1914 regarding success in artificially inseminating one out of eight queen bees worked with that summer. These investigators reported that, of the first 3,000 eggs laid by this queen, all but 4 proved to be worker eggs. She was wintered successfully (*16*), but in the spring she laid drone eggs as well as worker eggs and soon was laying drone eggs exclusively. After three weeks of drone laying she was dissected, but her spermatheca was found packed with living spermatozoa. In this work (*16*) the sperm from the drone was diluted with salt solution before being taken up in a fine pipette. The queen was then held in the left hand, while the pipette was introduced into the genital opening with the right hand and the sperm was forced out of the pipette by blowing with the mouth.

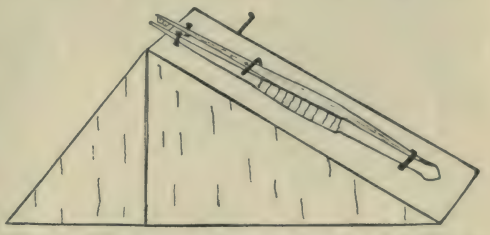


FIGURE 3.—Forceps and block used by Shafer in mating tests (Shafer)

During the next two years Howard and France (*16*) endeavored to carry this method further, but were successful with only 3 out of 55 queens. For one of the 3 success was gauged by the finding of sperm in the spermatheca upon dissecting the queen 26 days after the attempted insemination. One of the others laid only 5 per cent of worker eggs. In this work the sperm was not diluted with salt solution.

The success reported by Jager and Howard may have led Shafer (*45*) to his investigations in the same field. Shafer's main work was directed "through squeezing the drone—to evaginate the male organ into the vagina of the queen in the normal position." To keep the abdominal tips of the queen apart and to hold the sting out of the way in the process, a pair of forceps was mounted on one of the inclined surfaces of a triangular block in such a way as to allow the forceps to open only a quarter of an inch. (Fig. 3.) A small, thin plate was attached to one point of the forceps to aid in holding the sting back after the forceps had been introduced between the abdominal tips. A binocular microscope was used during the attempt at insemination.

Shafer later contrived a device which consisted of a No. 5 insect pin bent at right angles one-sixteenth inch from the head end and inserted firmly in a block. The pinhead could be inserted in the "sting notch" and as the queen's abdominal tips separated she could be moved so that the pin pressed against the sting and held it dorsalward. Shafer did not report any successful insemination, however.

In 1923 Quinn (*43*) announced success in artificially inseminating queens by a method which involves causing the drone to evert

its genital organs into proper position in the queen for the transfer of sperm to take place. No details of the method were published, but the actual operation appears to have been performed by his grandson, Harry Laidlaw, instead of by Quinn himself. In demonstrations witnessed by the writer in 1928 (*1*) and in the spring of 1930 (*8*), Laidlaw supported the queen with his left hand while making use of a pair of protractors to hold the abdominal tips apart, somewhat as did Shafer (*45*). The drone was held in the right hand while being caused to evert its organs in the proper position in the queen. No microscope was used.

In the summers of 1930 and 1931 Laidlaw was given temporary employment as field assistant by the Division of Bee Culture at its station in Baton Rouge, La. His work during 1930 led to the statement in the annual report of the Chief of the Bureau of Entomology (*24, p. 71*) that "the results obtained so far indicate that the method has considerable promise, for a partial degree of insemination can be effected in all cases." In December, 1931, Laidlaw reported before the American Association for the Advancement of Science that he had improved upon his technic somewhat, having devised a small spring to fit inside the queen's abdominal tips and hold them apart and having adopted the use of a microscope.

Apparently Laidlaw has been the only successful exponent of his method thus far, although, according to a recent statement (*2*), A. Z. Abushady, of Egypt, was successful in 1930 in inseminating three queen bees artificially without instruments. Unfortunately no details were given as to Abushady's work, however.

Malyschev (*23*), of Russia, in 1923 reported success obtained the year before in the artificial insemination of one queen bee. He dissected out the organs of a drone that had been caused to ejaculate by being chloroformed and placed them in the proper position in a queen that had been subjected to ammonia. Malyschev reported that this queen laid eggs normally in a nucleus and was then transferred to a queenless colony. He did not record her further history.

In October, 1926, Watson satisfied a special committee at Cornell University by a demonstration that he had developed a method which gave results far superior to any that had previously been published (*6*). According to his method (*49*)the sperm is injected with a microsyringe or pipette into the queen, which is bound to a small wooden block, or miniature operating table, hollowed out to fit her body. (Fig. 4.) The queen is held in position on the block by a thread passed several times around her thorax and the anterior part of her abdomen, the posterior tip of her abdomen being left free. The injection is accomplished under a binocular microscope.

To facilitate insertion of the microsyringe, Watson places a fine-pointed forceps between the queen's abdominal tips in such a way as to hold the sting back out of the way and to spread the tips. The microsyringe is held in a Barber pipette holder or micromanipulator which allows movement in three directions. Sperm is drawn in and is forced out of the tube of the pipette, which is about 0.5 mm in diameter, by a fine wire plunger moved by a screw. According to Watson's technic as first published (*49*), with the bulb of the drone held on the index finger of the left hand, the end of the pipette is

forced into the mucus and a small quantity is drawn in. The pipette is then forced more deeply into the bulb and the full load of sperm is taken up. In a well-developed drone the white mucus is readily discernible in one end of the bulb and the cream-colored sperm in the other end. The mucus is taken up first so that it will be forced out of the tube last and thus serve its purpose, as set forth by Bishop (*5*), of acting as a plug to the sperm owing to its property of congealing on contact with air.

In subsequent work Watson (*52*) minimizes the importance of the mucus plug, and describes a small "saculus" which is formed in the end of the bulb containing the sperm when pressure is applied at the other end. By cutting this sac and inserting the pipette there,

FIGURE 4.—L. R. Watson demonstrating his method of artificial insemination of queen bees. (Copyright by the American Bee Journal)

instead of pushing it through the mucus first, it is possible to take up in the syringe a large charge of sperm which contains practically no mucus.

As to his own success with his method, Watson (*52*) states that, of 42 queens operated upon in 1926, he found evidence, either by the microscope or by the rearing of worker brood, of some degree of insemination in about half this number. Of 96 queens operated upon in 1927, 65 per cent showed some degree of insemination, and 67 of 93 queens operated upon in 1928 showed some insemination. In a private communication to the writer, dated January 6, 1932, Watson stated that, out of 42 queens treated in 1929, 35 proved to be inseminated in some degree and that the remaining 7 were lost. In 1930 Watson, as reported by Disbrowe (*11*), operated on 40 queens. Nine of these queens were lost, but the remaining 31 showed some degree of insemination. About 12 appeared to be normally inseminated, while about 12 or 14 appeared to be only about 2 per cent inseminated. In 1931, according to the communication mentioned above, Watson treated 13 queens. Of these, 8 proved to be inseminated in some degree, 1 is recorded as a failure, and 4 were lost. Watson states that

" of the queens treated in 1931 only three, or possibly four, were anything like copiously inseminated."

To determine the degree of insemination with the aid of the microscope, Watson (*50*) compares the quantity of sperm in the artificially inseminated queen with that in the normally inseminated queen. The spermatheca of the normally inseminated queen at the beginning of egg laying is so filled with sperm that it is opaque, while that of the virgin queen remains filled with a clear liquid. It is, of course, difficult to judge accurately the degree to which the spermatheca is really filled, although with practice results can be obtained that will afford interesting comparisons.

One feat performed by Watson through his method was the transfer of living spermatozoa from the spermatheca of one queen to that of another (*50*). On another occasion he was able even to rear worker bees from eggs laid by a queen that had been artificially inseminated with spermatozoa from the spermatheca of a queen that had been mated a year before (*53*). To be able to transfer or to save in this way the spermatozoa contained in the spermathecae of queens mated with drones of certain desired strains or races should prove valuable at times in breeding work in preserving and propagating those strains or races.

The summer after Watson's discovery, Prell (*41*) announced that he, too, had successfully inseminated queen bees artificially by a method which, from the description given, seems to be like that used by Malyschev. Although Prell refers to Malyschev's work, he ascribes to him a method employing a pipette. Unfortunately, Prell gives no details as to the queens or the number with which he had success. He only reports that brood rearing began normally within a few days after the queens had been released. In a report of his work for 1928 Prell states (*42*) that in that year he attempted unsuccessfully to inseminate drone-laying queens. He did not state that he had been successful otherwise with his method during the year.

Apparently the first person to verify Watson's method was the writer (*32*). Within nine months from the time Watson had given publicity to his method, worker bees which were the offspring of a queen bee that the writer had subjected to the Watson method were emerging in the apiary of the bee culture laboratory of the Bureau of Entomology at Somerset, Md. The results of this work were not made public until the December meeting of the American Association of Economic Entomologists in the following year (1928), although the work had been mentioned previously by Alpatov (*3*) and by Hambleton (*15*).

The only other published reports of success by the Watson method are those by Mikhailoff, of Russia, and by Disbrowe, of Canada. Watson has informed the writer personally, however, that G. H. Cale also has performed the operation successfully, if a microscopic examination of the spermathecae of the queens may be used as a criterion.

During his first season's work on the artificial insemination of queen bees, conducted during the summer of 1928, Mikhailoff (*25*, *27*) performed 113 operations with apparatus made by himself in follow-

ing Watson's book (*49*) as a guide. In addition he performed 30 operations by Malyschev's method. These 143 operations were performed on only 105 queens, which means that some queens were treated more than once. Success was had in 18 instances, as was evidenced by the presence of sealed worker brood in 6 cases, and by spermatozoa found in the spermathecae of 12 queens. All-worker brood developed from the first eggs laid by 2 of the queens, but success in the case of 1 of these is attributed to the Malyschev method, because it was used on the queen after an apparently unsuccessful use of the Watson method 4 days earlier.

Mikhailoff (*26*) continued his experiments in 1929 with the aid of a helper, I. A. Licenko, and used a microsyringe made by Watson. During the year 114 queens were operated upon, some of them more than once, the total number of operations being 138. Twenty-four of the queens, or 21 per cent, showed some degree of normal insemination. Mikhailoff states that eight of these queens gave all-worker brood.

In 1930, according to a communication to the writer, Mikhailoff treated about 100 queens. These treatments were 27 per cent successful, as gauged from the actual rearing of worker brood. Of these successfully treated queens 10 per cent gave evidence of complete insemination.

Disbrowe's experiments date from 1929 (*9*). He states (*10*) that approximately 25 queens were operated upon during that season. Of this number more or less success was had with 5. In a later article (*11*) he mentions having continued the work in 1930, but gives no results.

BREEDING WORK AT THE BEE CULTURE LABORATORY

Work on a bee-breeding program was begun at the Bureau of Entomology's bee culture laboratory at Somerset, Md., before the announcement of Watson's discovery. A study, then under way, of queen rearing and of the biological and physical characteristics of the leading recognized races (*30*, *31*, *37*, *38*, *39*) was one step in this program. It was planned to make later a thorough trial of mating stations on the European model, but when Watson's method was made public it was considered advisable to test out methods of artificial insemination first and to endeavor to improve the technic of those found acceptable.

In any bee-breeding program, regardless of whether artificial or natural insemination is employed, there are numerous manipulations which must be carried on. Even when artificial insemination is used, it is not the greatest consumer of time in a large-scale breeding project. The manipulations belonging to the technic for breeding the honeybee under controlled conditions, whichever type of insemination is used, cover the maintenance, supply, and checking of the queens, drones, and workers used in the work. In the technic employed by the writer these manipulations include queen rearing to supply the necessary virgins, maintenance of nuclei to test the queens treated, marking queens, checking up on queens after the operation, maintenance of supply colonies both to rear queens and to provide honey and brood for nuclei as required throughout the season, making provision

to obtain sufficient drones of the right stock, marking drones, and other necessary operations. As beekeepers know, the successful carrying out of all this procedure is, in part at least, dependent on weather and floral conditions.

As commonly performed by the beekeeper or queen rearer, many of the manipulations just mentioned require too many bees, or too much time and equipment, to be economically or efficiently used in an intensive study of the genetics of the honeybee. Consequently the writer has endeavored to develop a technic for breeding the honeybee under controlled conditions which will permit the use of a maximum number of queens per queen breeder with a minimum requirement per queen of time, bees, and equipment. This technic, together with new technic for use with the Watson method of artificial insemination, is described in the text that follows. A discussion of the results obtained on queens used in the work on controlled mating is given first, however.

In this bulletin, unless stated otherwise, or unless specific reference is made to the spermatheca, the term " percentage of success " in connection with the writer's work refers to the percentage of worker cells in the first two weeks' total of sealed brood. As applied to the spermatheca, the term is used to denote the relative degree to which the spermatheca appears filled with sperm, as compared with the spermatheca of a normally inseminated queen. The actual emergence of worker or of queen bees is, of course, the final criterion for the purpose of the breeder or geneticist as to whether a queen is inseminated and as to the degree of insemination, but this gauge can not always be readily applied. Thus, when a queen lays few worker eggs in relation to the number of drone eggs, the actual emergence of the resulting workers is not always observed, and in such a case the story is told by the finding of worker cappings. When a queen is killed before she has laid any eggs, an examination of her spermatheca is the only way of determining whether or not she has been inseminated.

When a queen is laying mostly drone eggs and is using worker cells for them, it is sometimes easy on casual observation to mistake the cappings over the resulting pupae for worker cappings, but a little practice on the part of the observer should eliminate error from this source. On the other hand, spermatozoa may be found in the spermatheca of an artificially inseminated queen that has been injured sufficiently in the course of the insemination to prevent normal egg laying. Such an insemination could not be called successful from its utility in a genetical study, although it would be successful as far as the introduction of living spermatozoa within the spermatheca is concerned.

RESULTS OF ARTIFICIAL INSEMINATION

ON QUEENS USED IN 1927, 1928, AND 1929

In 1927, 20 queens were subjected to the Watson method by the writer. Positive results were obtained in 5 instances, including the completely successful case mentioned previously. For 1 of the other 4 queens the degree of success was 50 per cent, for 2 it was between 5 and 10 per cent, and for 1 it was below 5 per cent.

In 1928 experiments were conducted on 16 queens. Six of these queens were subjected to Watson's method and the last 3 were

inseminated successfully. In 2 cases the degree of success was over 70 per cent and in 1 it was 100 per cent. The other 10 queens were subjected to the Quinn-Laidlaw method, but without success. Since then the writer has done little with either this or the Malyschev method. Details on the work in 1927 and 1928, as well as the method of rearing the queen bees and handling them in the nuclei, are given elsewhere (*32*, *33*, *34*).

In 1929, 16 queens were operated on and placed in nuclei for observation. Of these, 1 was accidentally lost too soon to determine whether or not it had been inseminated, 4 were lost by balling or otherwise within 2 or 3 days after being put in the nuclei, 1 was lost 8 days later, and 2 were lost when their nuclei were robbed out within 3 days afterwards. This left only 8 queen bees on which to continue observations. Four of the 8 queens gave evidence of insemination, 2 of them beginning their egg-laying careers as if 100 per cent inseminated, while the other 2 appeared to be about 50 per cent inseminated.

ON QUEENS USED IN 1930

In 1930, 52 queens were operated upon by the Watson method. One other queen was operated upon by the Malyschev method, but she died from an undetermined cause too soon to ascertain the results. The data for each of the 52 queens are given in Table 1.

Sixteen queens received some degree of insemination, as was evidenced by the presence of emerging workers, worker pupae, or spermatozoa in the spermathecae of the queens. Success in the case of 10 of these queens was determined solely by observing under the microscope living spermatozoa in their spermathecae, in the case of 2 solely by observing worker pupae or emerging workers, in the case of 3 others by observing both sealed brood and sperm, and in the case of 1 by observing both emerging brood and sperm. These data alone show that insemination resulted in practically 31 per cent of the work in 1930.

Flat cells, which were undoubtedly those of worker brood, were observed in the case of 7 other queens. These cells did not occur in such abundance that workers were seen emerging, and such cells as were opened for observation did not contain brood old enough for the sex to be determined on superficial examination. A microscopic examination of 2 of these queens made, respectively, 33 and 124 days after insemination revealed no spermatozoa. The other 5 queens disappeared without such an examination having been made. If it is admitted that these 7 queens were also inseminated, the percentage of success for 1930 becomes 44.2 instead of being 31, as mentioned previously.

Of the remaining 29 queens, 5 (Nos. 4, 5, 9, 14, and 24) were found dead and 3 (Nos. 17, 22, and 27) had disappeared within 2 days of their attempted insemination. One queen (No. 1) died within 2 days of a second insemination attempted 14 days after the first one. Nine more queens (Nos. 10, 23, 25, 26, 28, 29, 33, 41, and 51) were found dead or had disappeared within 3 to 9 days of the attempted insemination. Queen No. 10 was found balled to death. Three others of the foregoing were given a second operation. Owing to other work, queens Nos. 1, 4, 5, 9, 10, and 14 were not examined under the miscroscope. One queen (No. 47) was killed accidentally on the seventh

TABLE 1.—*Record of queens operated on in 1930 by the Watson method* [1]

Queen No.	Cross [2]	Date of first insemination	Date of second insemination	Ether used	Type of plunger [3]	Drones used for first insemination	Drones used for second insemination	Age of queen at first insemination	Period between first and second inseminations	Period between last insemination and egg laying	Period lived after egg laying	Period lived after last insemination	Total length of life	Flatly sealed brood seen	Workers or virgins reared	Sperm seen in spermatheca
						Number	*Number*	*Days*	*Days*	*Days*	*Days*	*Days*	*Days*			
1	IXI	Apr. 26	May 10	X	G	1	?	7	14			2	23			
2	IXI	Apr. 30	Apr. 30	X	G	1	1	11	0	3	156	[4](159)	170	X		
4 [5]	IXI	May 3	May 3	X	G	1	1	10	0			2	12			
5	IXI	May 5		X	G	2		?				1	?			
6	IXI	do		X	G	1		?		10	2	12	?	X		
7	IXI	May 6		X	G	1		?		10	143	153	?	X	X	
8	IXI	May 7		X	G	1		?				19	?			
9	IXC	May 22		X	G	1		1				1	2			
10	IXC	May 28		X	G	1		5				8	13			
11	CXC	June 4	June 19	[6] X	G	1	1	7	15	3	34	(37)	[7] 59			X
12	CXC	do		O	G	1		7				36	43			
13	CXC	June 5		O	G	1		8				47	55			
14	CXC	do	June 5	X	W	1	1	9	0			2	11			
15	CXC	June 6		X	W	1		?				[7] 45	?			O
16	CXC	do		X	W	1		10		7	117	(124)	[7] 134	X		O
17	CXC	June 10		X	G	1		?				2	?			
18	CXC	June 13		X	G	1		15				38	53			
19	IXC	do		X	W	1		21				1	22			X
20	CXC	June 18		O	G	1		21		10	23	(33)	[7] 54	X		O
21	CXC	do		O	G	1		22				33	55			
22	IXC	June 19		X	W	1		?				2	?			
23	IXI	June 20		X	W	1		4				5	9			O
24	IXC	June 23		X	W	1		7				1	8			O
25	CXC	June 30	June 30	X	G	1	1	8	0			3	11			O
26	CXC	July 1	July 1	X	G	1	1	8	0			7	15			O
27	CXI	July 2	July 2	X	G	1	1	9	0			1	10			
28	CXI	July 3	July 3	X	W	1	1	10	0			7	17			O
29	CXI	July 7		X	W	1		13				3	16			O
30	CXI	July 8	[8] July 8	O	W	1	1	14	0			1	15			X
31	CXI	July 9		O	W	1		15				2	17			X
32	CXI	do		O	G	1		13				12	25			
33	CXI	July 10		O	W	1		14				5	19			
34	CXI	do		O	W	1		13				11	24			X
35	CXI	do		O	W	1		15				17	32			O
36	CXI	July 11		O	W	1		16				10	26			
37	CXW	July 14		O	W	1		18		24	62	(86)	[7] 104	X		X
38	CXW	July 15		O	W	1		18		23	68	(91)	[7] 109	X		X
39	CXW	do		O	W	1		19		28	23	(51)	70	X		

40	7-1×W	do		O	W	1		8				17	25				
41	7-1×W	July 17		O	W	1		22				4	26				
42	W×W	July 18		O	W	2		10		6		?	?	X			
43	7-1×W	do		O	W	1		10				6	16				X
44	7-1×C	July 23	July 25	O	W	1	1	15	2	12	98	(110)	[7] 127	X	X		X
45	7-1×I	do		O	W	1		15		14	109	(123)	138	X	X		
46	7-1×I	July 24		O	W	2		17				4	[9] 21				X
47	7-1×I	July 25		O	W	1		9				7	[9] 16				
48	7-1×I	July 28		O	W	2		20		30	9	(39)	[7] 59	X			X
49	I×I	July 31		O	W	3		31		12		18	61	X			
50	I×I	do		O	W	2		31				9	[7] 40				X
51	I×?	Aug. 1		O	W	?		32				9	41				
52	I×I	Aug. 4		O	W	5		22				1	[9] 23				X
53 [10]	I×I	Aug. 5		O	W	3		22				1	[7] 23				X

[1] X indicates positive, O, negative results, except in column headed "Ether used," in which X indicates that ether was used, and O that ether was not used.
[2] The first symbol used refers to stock of queen; second symbol to stock of drone. I=Italian, C=Caucasian, W=white-eyed Italian, 7-1=F_1 generation of queen No. 7.
[3] G=glass; W=wire.
[4] Numbers in parentheses not included in total length of life.
[5] Queen No. 3 was operated on by Malyschev method.
[6] No ether was used in first insemination.
[7] Killed for dissection.
[8] Two additional operations on this queen were made on this date.
[9] Killed accidentally.
[10] Actual total is 52.

day after the operation, but when found her spermatheca had dried out too much for proper examination. Queen No. 35 survived 15 days after the attempted insemination and was 1 of 7 of the foregoing for which negative results were obtained under the microscope.

The remaining 9 queens lived from 10 to 47 days after their operations without showing any evidence of insemination. Four of these 9 queens (Nos. 12, 13, 21, and 40) disappeared; 1 (No. 36), when found, was too dry for examination, while the spermathecae of 3 (Nos. 8, 18, and 32) were not examined microscopically. No sperm was seen in the spermatheca of queen No. 15.

In only 1 (No. 45) of the 3 queens from which workers or queens were reared in 1930 did all-worker brood develop. Queen No. 52, however, which was killed accidentally on the day after the operation, proved to contain such a large quantity of living spermatozoa in her spermatheca as to warrant the assumption that all or practically all her brood would have been workers, at least in the early stages of her egg laying.

In the case of most of the other 13 queens in whose spermathecae living spermatozoa were found, the degree of insemination appeared relatively small. Five of these queens were in hives 4 days or less after being inseminated, while one was in a hive only 9 days. As this period was scarcely long enough for these queens to begin egg-laying, there was no opportunity to determine the degree of insemination from the quantity of worker brood reared. Worker bees had been reared from one (No. 44) of these queens, however. The examination of the spermatheca of this queen was made more than 3 months after the insemination. Although flat-sealed cells were found on brood reared from queens Nos. 37 and 38, no worker pupae or emerging workers were observed. On examination 80 days after insemination the spermatheca of No. 37 had a light, milky appearance and living spermatozoa were found, while 91 days after insemination the spermatheca of No. 38 showed that the sperm had collected into a small spherical mass floating in the clear spermathecal liquid.

Another interesting case was that of a queen (No. 48) born on July 8 and inseminated on July 28. On September 5 only 5 flatly sealed cells were found out of a total of 150 sealed. The queen was killed, and on examination of her spermatheca a spherical mass of sperm much larger than in the case of No. 38 was seen floating in the clear liquid which ordinarily characterizes the spermatheca of an inseminated queen bee. Further examination showed living spermatozoa to be present. Such cases are quite comparable to that of the queen bee operated upon by Jager and Howard, which, as mentioned earlier, contained spermatozoa in her spermatheca even after she had been laying only drone eggs.

Another queen (No. 11) was born on May 28 and inseminated on June 4. No eggs being seen in the meantime, she was reinseminated on June 19. Eggs were seen on June 22 but, although larvae were seen later, none of these were found to develop into adults. The queen was killed on July 26 and, although her spermatheca showed only a slight degree of cloudiness, living spermatozoa were discovered.

In queen No. 19 the sperm was found massed within the spermatheca in a shape like a smoke ring which revolved rapidly. This queen and queens Nos. 52 and 53 were the only ones whose spermathecae appeared under the microscope to be more than 10 per cent filled with spermatozoa. Of these three, the spermatheca of No. 52, as mentioned earlier, appeared to be well filled, or between 75 and 100 per cent. That of No. 19 appeared to be at least 20 per cent filled, while that of No. 53 appeared to be 10 to 20 per cent filled. The spermatheca of the queen which produced all-worker brood (No. 45) was not examined microscopically.

ON QUEENS USED IN 1931 AND 1932

In 1931 a total of 103 queen bees were treated, 97 by the Watson method and 6 by the Malyschev method. (Table 2.) Of the latter, 5 disappeared within 1 to 29 days after the performance of the experiment, while the spermatheca of the sixth (No. 11) showed negative results under the microscope.

Of the 97 queens on which the Watson method was used in 1931, both queens and workers were readed from 8, or 8¼ per cent. Workers but no queens were reared from 3 others, thus making 11 queens, or 11⅓ per cent of those treated, from which the F_1 generation was reared. As indicated by the proportion of sealed drone to sealed worker cells which were found, some of these queens (Nos. 5, 12, 33, 34, 37, and 51) laid no drone eggs; others (Nos. 47, 79, and 84) laid only a very small proportion in relation to worker eggs—no more, however, than certain normally inseminated queens in neighboring colonies; while about half the eggs laid by 2 (Nos. 78 and 82) proved to be drone eggs. Of the 11 queens, 5 (Nos. 51, 78, 79, 82, and 84) were alive and laying at the end of the brood-rearing season and entered the winter of 1931–32.

In addition to the 11 queens successfully inseminated as evidenced by the production of F_1 queens or workers, the spermathecae of 25 other queens lost by balling, by accident, or otherwise were found to contain living spermatozoa. This makes a total of 36 queens inseminated, or slightly more than 37 per cent of indisputable insemination for the season. If to this total are added 2 queens (Nos. 30 and 48) whose only indication of being inseminated was the presence of some flatly sealed cells among their brood, the grand total for 1931 becomes 38, or slightly more than 39 per cent of successful insemination. These last 2 queens, however, laid relatively few eggs, although sufficient to have rendered possible a continuation of their particular strain under favorable circumstances.

Of the 25 queens whose degree of insemination was determined from their spermathecae, the spermathecae of one-fifth (Nos. 4, 29, 53, 86, and 89) were estimated to be 50 per cent or more filled with sperm, those of about one-sixth (Nos. 45B, 52, 59, and 93) to be 25 per cent or more filled, those of more than one-fourth (Nos. 3, 21, 40, 42, 71, 80, and 81) to be 10 per cent or more filled, while those of slightly more than the remaining third (Nos. 8, 10, 20, 22, 24, 44, 46, 88, and 99) were estimated to be less than 10 per cent filled. Flatly sealed brood was found in 2 of these cases (Nos. 10 and 20), although no emerging adults were seen.

TABLE 2.—*Record of queens used in 1931* [1]

Queen No.	Cross [2]	Date of first insemination	Date of second insemination	Date of third insemination	Type of plunger or method used [3]	Drones used for first insemination	Drones used for second insemination	Drones used for third insemination	Age of queen at first insemination	Period between first and second inseminations	Period between second and third inseminations	Period between last insemination and egg laying	Period lived after egg laying	Period lived after last insemination	Total length of life	Flatly sealed brood seen	Workers or virgins reared	Sperm seen in spermatheca
						Number	*Number*	*Number*	*Days*	*Days*	*Days*	*Days*	*Days*	*Days*	*Days*			
1	CXI	May 3			W	2			13					5	18			O
2	CXI	May 5	June 4	June 12	W	2	1	2	4	30	8			10	52			
3	CXC	May 6			W	2			16					9	25			X
3A	CXC	May 15			W	3			14					1	15			O
4	CXC	May 18			W	2			6					2	8			X
5	CXC	May 18			W	2			6			14	5	[4] (19)	25	X	X	
6	CXC	May 19			M	1			6					3	9			
7	CXC	May 19	June 4		W	1	1		6	16		7		11	40	O	O	O
8	CXC	May 19	May 20		W	1	1		6	1				6	13			X
9	CXC	May 20			W	1			7					7	14			
10	CXC	May 20			W	1			8			13	163		184	X		X
11	CXC	May 20			M	1			8					9	17			O
12	CXC	May 21	June 5		W	1	1		6	15		3	98	(101)	122	X	X	X
13	CXC	May 22			W	2			7					10	17			
14	CXC	May 22	May 23		M	1	1		7	1				1	9			
15	CXC	May 25			W	2			10					8	18			
16	CXC	May 28	June 5		M	1	2		11	8		10	4	(14)	33			
17	CXC	May 28			M	1			12					7	19			
18	GXI	June 3			W	2			7					23	30			
19	CXC	June 3			M	1			21					29	50			
20	CXC	June 5	June 29		W	2	1		1	24		18	110	(128)	153	X		X
21	CXC	June 5			W	2			1					5	6			X
22	CXC	June 8			W	1			3					1	4			X
23	CXC	June 8			W	1			3					4	7			
24	CXC	June 10			W	1			5					3	8			X
25	CXC	June 11			W	1			6					2	8			O
26	CXC	June 11			W	2			6					7	13			
27	CXC	June 11			W	2			6					5	11			
28	CXC	June 12			W	2			7					14	21			
29	CXC	June 12			W	1			7					1	8			X
30	CXC	June 12	June 12		W	3	1		7	0		29	96	(125)	132	X		O
31	CXC	June 15			W	1			10					28	38			O
32	GXI	June 18			W	2			14					11	25			O
33	CXI	June 19			W	2			14			6	34	(40)	54	X	X	?
34	GXI	June 22			W	2			[5] ?			12	9	(21)	?	X	X	X
35	CXC	June 23	June 23		W	1	1		7	0				10	17			O

36	C×C	June 23	June 23		W	1	1		7	0				6	13							
37	C×C	[5] ?	[7]June 23		W	?	1		[6] ?	?		15	12	(27)	65	X	X	X				
38	C×C	June 24			W	1			7			17	6	(23)	30	O	O	O				
39	C×I	June 24			W	1			2					1	3			O				
40	C×I	June 24	June 24		W	1	1		2	0				2	4			X				
41	C×C	June 25			W	1			3					7	10			O				
42	C×I	June 25	June 25		W	1	2		3	0				2	5			X				
43	C×I	June 26			W	1			4					7	11			O				
44	C×I	June 26			W	2			4					4	8			X				
45	C×C	June 29			W	2			7					12	19			O				
45A	C×C	[5] ?			W	?			[6] ?					?	15			O				
45B	C×C	[5] ?			W	?			[6] ?					?	15			O				
46	12-1×C	July 1	July 2		W	1	1		6	1				7	14			X				
47	C×C	July 3			W	1			29			8	90	(98)	127	X	X	X				
48	C×C	May 4	July 3		W	1	1		14	60		12	30	(42)	116	X						
49	C×C	[5] ?	[8]July 6		W	?	1		[6] ?	?				9	40							
50	C×C	[5] ?	[8]July 6		W	?	1		?	?				14	45							
51	C×C	[5]July 9	(9)		WG	?	1		?	?		12			[10]	X	X					
52	C×C	[5] ?	[7]July 13		W	?	1		[6] ?	?				7	45			X				
53	C×C	June 18	July 9	July 13	W	1	1	1	13	21	4			11	49			X				
54	I×C	July 17			W	1			3					7	10							
55	I×Ch	July 15	July 21		G	1	1		2	6				3	11			O				
56	I×C	July 16	July 16	July 21	G	2	1	1	3	0	5			10	18							
57	Cp×C	July 30	Aug. 5	Aug. 6	W	2	1	1	7	6	1			7	21							
58	12-1×I	Aug. 4			W	1			6					8	14							
59	47-1×C	Aug. 6			W	1			6					21	27			X				
60	47-1×C	Aug. 6			W	1			6					6	12			O				
61	47-1×C	Aug. 6			W	1			6					6	12							
62	I×C	Aug. 7			W	1			9					4	13			O				
63	G×I	Aug. 7			W	1			9					8	17							
64	51-1×C	Aug. 10			W	1			5					5	10							
65	51-1×I	Aug. 10			W	1			5					3	8			O				
66	G×I	Aug. 10			W	1			5					23	28			O				
67	51-1×C	Aug. 13			W	2			8					14	22			O				
68	51-1×C	Aug. 13			W	1			7					14	21							
69	51-1×I	Aug. 14	Aug. 14		W	1	1		8	0				1	9			O				
70	51-1×I	Aug. 14			G	1			8					20	28							
71	G×I	Aug. 14			W	1			16					16	32			X				
72	G×I	Aug. 14			W	1			8					13	21			O				
73	51-1×I	Aug. 18			W	1			8					12	20							
74	47-1×C	Aug. 19			W	1			8					8	16							
75	51-1×I	Aug. 24	Aug. 24		W	1	1		13	0				11	24							
76	47-1×C	Aug. 24	Aug. 24		W	1	1		14	0				11	25							
77	47-1×C	Aug. 24	Sept. 21		W	1	2		13	28					[11]							
78	47-1×I	Aug. 24			W	1			13						[11]	X	X					
79	I×I	Aug. 26			W	1			21			9			[11]	X	X					
80	I×C	Aug. 27			W	1			19					3	22			X				
81	I×I	Aug. 28	Sept. 23		W	1	3		19	26				0	45			X				
82	I×I	Aug. 28			W	1			21			6			[11]	X	X					
83	47-1×C	Aug. 28	Aug. 28		W	1	1		13	0				10	23							

See footnotes at end of table.

TABLE 2.—*Record of queens used in 1931* [1]—Continued

Queen No.	Cross [2]	Date of first insemination	Date of second insemination	Date of third insemination	Type of plunger or method used [3]	Drones used for first insemination	Drones used for second insemination	Drones used for third insemination	Age of queen at first insemination	Period between first and second inseminations	Period between second and third inseminations	Period between last insemination and egg laying	Period lived after egg laying	Period lived after last insemination	Total length of life	Flatly sealed brood seen	Workers or virgins reared	Sperm seen in spermatheca
						Number	*Number*	*Number*	*Days*	*Days*	*Days*	*Days*	*Days*	*Days*	*Days*			
84	I×C	Aug. 29			W	1			19			18			(11)	X	X	
85	51–1×I	Aug. 31			W	1			22					1	23			O
86	G×C	[5] ?	Aug. 31	Sept. 1	W	1	1		?	26	1			1	27			X
87	G×C	Sept. 1			W	1			20					16	36			
88	37–1×I	Aug. 17	Aug. 25	Sept. 1	W	?	?	1	14	8	7			7	36			X
89	47–1×I	Sept. 4			W	1			11					3	14			X
90	51–1×I	Sept. 8	Sept. 8	Sept. 9	W	1	1	1	14	0	1			11	26			
91	51–1×C	Sept. 9			W	1			15					1	16			O
92	51–1×C	Sept. 10	Sept. 10		W	1	1		16	0					(10)			
93	47–1×C	Sept. 16	Sept. 16		W	2	1		17	0				6	23			X
94	47–1×C	Sept. 16	Sept. 16	Sept. 16	G	1	1	1	8	0	0			36	44			
95	82–1×I	Sept. 29			W	1			6					5	11			O
96	82–1×I	Sept. 30			W	2			7					36	43			
97	82–1×C	Oct. 1			W	2			8					20	28			O
98	82–1×C	Oct. 6			W	1			13					4	17			
99	47–1×C	Oct. 15			W	2			17					8	25			X
100 [12]	79–1×I	Oct. 15			W	1			15					21	36			

[1] X indicates positive, O negative, results.

[2] First symbol refers to stock of queen; second symbol to stock of drone. C=Caucasian; Ch=Chinese; Cp=Cyprian; G=German brown; I=Italian; 47–1, etc.=F_1 generation of queen No. 47, or of queen represented by first number.

[3] G=glass (Watson); W=wire (Watson); M=Malyschev method.

[4] Numbers in parentheses not included in total length of life

[5] Put in a nursery cage after operation and no record taken.

[6] Virgin used came from other than queen-rearing colony.

[7] 38 days old at second insemination.

[8] 31 days old at second insemination.

[9] 34 days old at second insemination.

[10] Still alive on Nov. 1, 1931, but missing on Feb. 10, 1932.

[11] Still alive on Feb. 10, 1932.

[12] Actual total is 103.

Of the 59 queen bees operated upon by the Watson method in 1931 and for which no positive results are recorded, the spermathecae of 26 proved to be clear on examination. Two of the remaining 33 queens were inseminated late in the year, and in the slackening of brood rearing, which occurred soon after all were successfully introduced, the results of the attempted inseminations were not determined. These queens, however, were still in their nuclei at the beginning of winter. The spermathecae of the other 31 queens were not examined microscopically.

Although the season is not yet over, it seems in order to state that 353 queens were subjected to the Watson method in 1932 before September. With two exceptions only one operation was given each. In the two exceptions two operations were given but neither proved successful. Of the 353 queens, 115, or nearly one-third, were successfully inseminated. From 43 of the 115, adult workers or queens, or both, were reared. The majority of the 43 laid only worker eggs. The egg-laying performance of some of them could not be differentiated from that of naturally inseminated queens. Certain of these queens were given 10 frames. As about 50 queens yet remain to be checked, the total number of successes for the season should prove somewhat higher than that just given.

NEW INSTRUMENTS AND METHODS FOR ARTIFICIAL INSEMINATION

In 1927 the technic originally described by Watson was carried out in the main, with some minor exceptions. For instance, no attempt was made to feed the queen while she was bound to the operating block, as the writer has repeatedly observed that the queen bee can go without food with no apparent injury during the time required for the operation. Illumination was obtained by using a standard microscope lamp and at times even an ordinary desk lamp without any special reflector or filter. A microscope lamp is still being used and is brought as near the queen as necessary for sufficient illumination during the operation. No ill effects from heat have been detected. In private discussion with the writer Watson stated in 1931 that he now uses a lamp that is attached to his microscope.

GLASS HOLDER

In 1928 the first major modifications in the technic were made. One of these, as described elsewhere (*32*, *33*), does away with the necessity of binding the queen down with thread to the operating table. A small glass tube, devised by Jas. I. Hambleton, is used instead. The queen is backed into this tube until her abdomen projects just far enough from the narrowed opening at the other end for the operation to be performed. A stopper formed of another piece of glass tubing prevents her escape once she is in position.

As originally described, the glass stopper was held in the outer tube by a small wooden wedge. The writer later adopted the plan of dipping the end of the stopper in melted paraffin so that a coating is formed which will serve to retain the stopper in the outer tube when it is shoved in the desired distance. In hot weather it may be necessary to recoat the stopper frequently if paraffin with too low a melting point is used, and, at times, the wooden wedge can be used

in addition. It has been found most convenient of all, however, to fasten the stopper in place by a small piece of DeKhotinsky cement. The stopper is thus held firmly in place during the operation and is easily loosened by turning it enough to crack the cement.

FIGURE 5.—Glass holder supported on wooden block

The writer has found that the queen is easily made to back into the tube by letting her first run into another similar tube. When her head touches the constricted end she usually begins to back of her own accord, and if the two tubes have been brought together in the meantime, she will continue backing until she is in proper position in the holder.

MOUNT FOR GLASS HOLDER

At first the glass holder was mounted on a triangular wooden block (fig. 5), which permitted an elevation at three different angles. The tube could be turned to any desired angle in the plane of the face of the block on which it rested, because it was bound to the block only by rubber bands. Such a block serves very well.

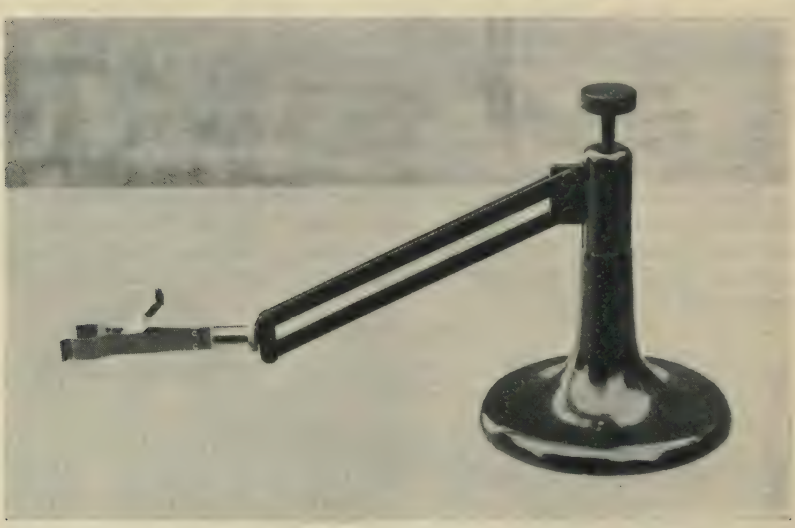


FIGURE 6.—Mount for glass holder with queen shown in holder

In 1931 the wooden block was discarded in favor of a standard dissecting lens stand. (Fig. 6.) This apparatus, entirely of metal, consists of a long arm fitted to an upright rod by a rack and pinion, the upright itself being supported by a heavy base. At the end of the arm is a revolvable clamp which holds the glass tube and permits it to be turned about the arm as an axis. The tube can also be readily

set at any desired angle in relation to the arm, since it is held only by pressure from the two sides of the clamp.

In 1932 a different type of mount was devised which is now used exclusively. Included in its construction (fig. 11) is a narrow strip of wood with a hole in each end through which passes an upright metal rod. The strip can be readily pushed up and down on these rods, but yet fits tightly enough on them to stay at any desired height. Through the center of this strip is a narrow slot about 2 inches long for the insertion of a thumbscrew which also passes through a smaller wooden block. The thumbscrew is provided with a wing nut for fastening the two blocks firmly to each other at any vertical angle. The slot permits a certain horizontal adjustment of the smaller block in the lengthwise direction of the long block. The glass holder fits into a hole through the smaller block, and can be rotated in it. To hold the tube in the desired position in this hole, a thumbscrew is provided. Since this mount allows the holder to be

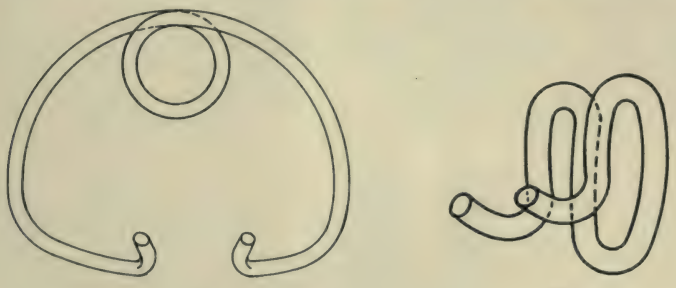


FIGURE 7.—Clips: A, Old type; B, new type. Both enlarged

adjusted in position for height, to be rotated on its own longitudinal axis, to be revolved in a vertical plane, and to be moved for a limited distance horizontally in the lengthwise direction of the longer block, ample provision is made for bringing the glass holder into proper position in relation to the pipette.

SPREADING AND HOLDING ABDOMINAL TIPS

CLIP

Another innovation dating from 1928 was the use of a U-shaped clip of fine wire with each end bent at a right angle to form a small prong. These prongs were so inserted as to hold the abdominal tips of the queen bee apart while the pipette was manipulated into position. The sides of the U were bowed outward to give some tension and, when the prongs were in position between the abdominal tips, projected at right angles from the queen. Instead of making a simple U-bend in the clip, the writer later found it advisable to secure more tension by making a small loop at what corresponds to the bottom of the U. (Fig. 7, A.)

Such a clip was first suggested by L. C. Spencer, of Louisiana, for use with the Quinn-Laidlaw method, but, as described earlier (*32*, *33*), its use with the Watson method has proved more convenient than using a pair of forceps for the same purpose. This type of clip, however, possibly owing to the wire used, proved a trifle too heavy,

since movements of the queen often caused it to swing downward with the points of its prongs serving as pivots and then to drop out at inconvenient moments.

In 1931 the writer devised an entirely new type of wire clip which stays when put in position. It is U-shaped with the two sides of the U straight and bent back on themselves nearly as far as the closed end. At this point the rebent sides are bent upward at right angles and are left just long enough to be grasped conveniently with the points of a fine dissecting forceps. The width of this clip approximates the lateral width of the vestibule of the queen, while the length is approximately the height of the vestibule when the queen's abdominal tips are spread apart. (Fig. 7, B.)

The clip is easily introduced between the queen's abdominal tips. During this procedure it is held in a pair of dissecting forceps. With the point of a transferring needle the abdominal tips are first spread apart just enough to permit the insertion of the closed part of the U between the sting and the dorsal abdominal tip. Then, by pressing against this tip with the closed end of the clip and by pressing at the same time against the ventral abdominal tip with the transferring needle, the tips are spread far enough apart so that the sides of the clip can be dropped down within the sides of the vestibule. (Fig. 8.)

When in position the rebent ends of the sides of the clip rest against the queen's ventral abdominal tip, while the closed end of the clip rests against her dorsal abdominal tip. The base of the clip rests on the membranous covering of the posterior end of the body cavity. The pressure of the tips plus that of the sides of the vestibule holds the clip in this position regardless of respiratory movements by the queen. The swinging movement, which was an objectionable feature of the older clip, is absent. The sting and sting palpi are free, but, possibly owing to stretching of sides or ends of the vestibule, remain out of way and at the same time are kept from injury to themselves.

HOLDING HOOK

In connection with the clip, the writer in 1930 introduced the use of a teasing needle with its point bent at a right angle to form a hook. By means of this needle, or holding hook, the queen's ventral abdominal tip is pulled to the left the desired distance when the pipette is brought within the vestibule. The clip may be removed at this time since the pipette itself then serves to hold the queen's dorsal abdominal tip to the right. The sting remains out of way between this tip and the pipette. In 1931, as a means for keeping it in the proper position without holding it by hand, the hook was fastened to an adjustable clamp mounted on a supporting rod. When thus held it is easily brought into place by moving the base to which the rod is attached.

In 1932 a method was devised for spreading and holding the queen's abdominal tips apart by the use of two holding hooks alone. In connection with the mount devised that year for the glass holder, a small wooden block to support a holding hook (fig. 11) was attached to each of the two metal rods. These blocks can be shoved up and down or be turned on the rods, but fit tightly enough to stay in the desired position. The holding hooks resemble teasing needles,

having wooden handles and points of fine spring wire bent in proper shape to hold the abdominal tips of the queen without injuring her. The handle passes through a hole in the block large enough for freedom of movement in inserting the hook between the queen's abdominal tips, while a thumbscrew is provided to fasten it securely in position. The ventral abdominal tip is held by one hook and the dor-

FIGURE 8.—Inserting the clip

sal abdominal tip by the other. Thus, merely by means of these two holding hooks the tips are easily spread and held apart the proper distance and the clip is eliminated altogether. When the pipette is in position, the hook holding the dorsal tip can be withdrawn.

In the procedure just described the combined use of two hooks, or of a hook and a clip, does away with the need of a forceps during the insertion of the pipette, and the queen's genital opening is

more readily located than when her abdominal tips are kept apart by a pair of forceps held by hand. Consequently, this procedure speeds up the bringing of the pipette into proper position in relation to the genital opening, and permits the operator to leave the microscope during the operation at any time after the insertion of the

FIGURE 9.—View of apparatus during insemination of queen with technic as modified in 1931

pipette and, on returning, to find relatively the same view still under the microscope, provided the queen has not had too great freedom of movement. The view presented in the field of the microscope is the following: At the right, the pipette; in the center, the end of the queen's abdomen protruding from the glass holder with her dorsal abdominal tip at the right and her ventral abdominal tip at the left; and, at the extreme left, the hook. (Fig. 9.)

MULTIPLE SET-UP

The time required for the part of the insemination accomplished under the microscope varies considerably, depending upon the quantity of sperm in the pipette, how properly the pipette has been inserted in the queen, how rapidly the sperm is forced out of the pipette, and similar factors. Sometimes the insemination has been completed in half an hour, but often it has taken longer. This does not include time spent in getting the queen ready for the operation, filling the pipette, and other preliminary manipulations.

FIGURE 10.—Unit of multiple set-up at first devised in 1932. There is shown the microscope, false stage, new pipette manipulator, rod support for manipulator, micropipette, glass holder for queen but without queen, mount for glass holder, holding hook with its support, and new-style lamp

From experience thus far, the writer prefers that the operation should not be hurried. During the actual operation the screw of the pipette is turned slowly for the purpose of forcing the sperm out just fast enough for it to enter the queen without leaking back out. If it does begin to leak, the operation is stopped to allow the sperm and mucus exposed to the air to harden, as described later under the heading "Mucus Plug." For this and other reasons, the operator must often wait during the operation before proceeding further.

In order to utilize any extra time on hand during an operation, the use of a multiple set-up for the work in 1932 was adopted so that several queens might be operated upon more or less simultaneously. This multiple set-up contains several individual units (fig. 10), each of which consists of the apparatus used in the artificial insemination of a queen. To reduce the expense of each unit, however,

and to provide greater convenience in the work, the writer devised a pipette manipulator and also a false stage which is not attached to the microscope but yet serves as the base for the support of the manipulator. The stage and manipulator are described under separate headings. The method of holding each individual queen is that already described which permits the operator to leave the microscope once the pipette is properly inserted in the queen. The false stage is so constructed that, even if the Barber micromanipulator is used, only one miscroscope and one lamp are needed for the entire set-up regardless of the number of units. The writer's equipment, however, includes a lamp for each unit because it is much more convenient and saves time.

By the use of a multiple set-up any tendency to hurry the operation should be reduced because the operator has more than one queen with which to occupy his time. The number of queens to be provided for in one set-up will depend upon the skill and convenience of the operator. The set-up used by the writer in 1932 consisted of six units.

FALSE STAGE

In the writer's equipment for work with the Watson method in 1932, instead of the false stage pictured in Figures 9 and 12, which slips tightly over the base of the microscope stand and holds the Barber micromanipulator, there is used a stage (figs. 10 and 11) made of a sheet of metal supported at each end by wooden blocks of a height sufficient for the base of the microscope stand to be slipped in and out readily beneath the stage without touching it. Instead of using wooden blocks for supports, the sheet of metal may be bent at each end for this purpose. If the Barber micromanipulator is used, provision is made for attaching a removable support for it, while for the pipette manipulator described in the next section provision is made for attaching to the stage the rod which supports the manipulator. This stage is made long enough to attach to it the rod for the holding hook at the left of the operator, or to serve as a base for the support of the holding hook in case a movable support is used. It is also long enough not to tip up if the Barber micromanipulator is being employed with it, but is not wide enough to hold the lamp or the base of that type of mount for the glass holder shown in Figure 6. If desired, it can be bolted or clamped to the table or other support on which it rests. When the stage is equipped with a rod at the right for the new pipette manipulator (fig. 11), and one at the left for the holding hook, these two rods also serve to hold the new mount devised for the glass holder in 1932. In the multiple set-up these stages are placed in a row, or otherwise, for conveniently transferring the microscope from one to the other, as well as to provide for shifting the miscroscope lamp if only one is used.

PIPETTE MANIPULATOR

The new pipette manipulator devised by the writer in 1932 consists of two small oblong wooden blocks joined together by a thumbscrew and wing nut which permits fastening the two pieces at various angles in relation to each other. (Fig. 11.) One of the blocks is made into a clamp which is fitted to an upright rod attached to

the false stage. By means of another bolt and wing nut this clamp can be fastened firmly at any height on the rod and at any horizontal angle. Through the free end of the other block is a hole just large enough to permit the pipette to be shoved through freely, a small screw being provided to fasten the pipette at the proper position. An additional clamp just beneath that holding the manipulator on the rod serves to hold the manipulator at the proper height when rotating it in a horizontal plane.

The rod supporting these clamps is threaded at one end. This end is passed through a hole in the false stage and a nut fitted to it permits fastening the rod rigidly in place. If this rod and another for a holding hook are fastened to separate bases like those used for

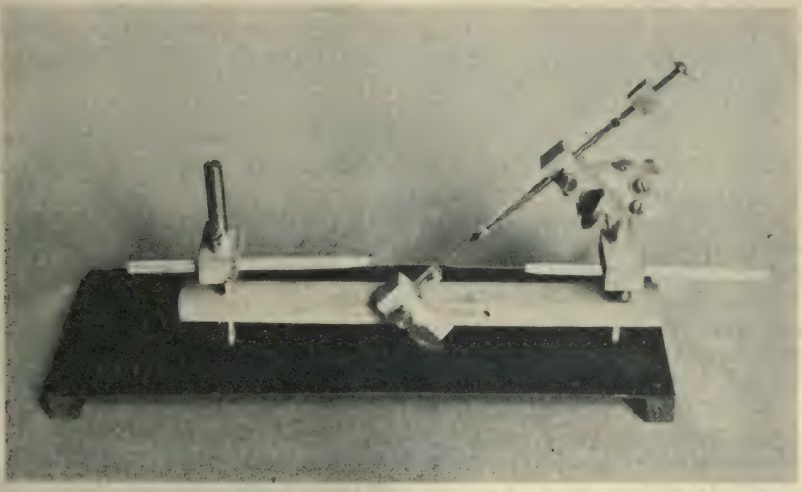


FIGURE 11.—Equipment devised and used by writer in 1932, showing false stage, mount for glass holder, two holding hooks and their mounts, and pipette manipulator with extra clamp just beneath it on its supporting rod. The pipette is slightly modified from the standard Watson type as regards the style of activating screw and the fact that it passes through a wooden instead of a metal cap fitted over the outer glass sheath

the holding hook in 1931 (fig. 9), these two rods can be used as a support for the new type of mount for the glass holder (fig. 11) devised in 1932 and the stage may be dispensed with. However, the writer has found it more convenient to use the false stage, since it is more rigid and lessens the strain on the long strip of the mount. It is possible to operate the new manipulator when its supporting rod is mounted on a separate base alone in conjunction with the mount for the glass holder used in 1931 (fig. 6) and a separate base for a holding hook, but the lack of rigidity plus the risk of hitting either base with the microscope or body makes this arrangement much less desirable than the use of the false stage.

This type of pipette manipulator evidently does not give so fine an adjustment as does the Barber micromanipulator, but its cost is negligible, and, if properly made, it will serve the purpose if used by a person with a steady hand. It has the further advantage of rotation in a vertical plane. It was the only manipulator used by the writer in 1932.

PIPETTE

At one stage of the work it seemed desirable to use in the microsyringe a glass tube of smaller diameter than the one furnished by Watson. A smaller pipette meant using a correspondingly smaller plunger. After some experimenting in 1929, glass tubes of less than half the diameter of those furnished by Watson were made and fitted with glass plungers (*34*). All the writer's work in 1929 was carried out with such pipettes. In 1930, 20 queens (Table 1) were operated on with them, and 5 in 1931. (Table 2.) Some success was had.

Watson had experimented with glass plungers but gave them up because he considered them too fragile (*49*). He attempted to wind his glass plungers with thread to secure better suction, whereas the writer has had success in using them unwrapped.

For use with the small tubes glass plungers present certain desirable features, among these being their rigidity when in the tube and the ease with which they can be drawn out from a piece of glass rod to fit any such tubes. On the other hand, the tubes can be drawn to fit the plungers. One end of the plunger is carefully smoothed off in a flame and the other end is fastened by DeKhotinsky cement directly onto a glass stem drawn out to the proper shape to permit the spring to act on it. Otherwise, construction of these small pipettes is the same as that in the standard Watson pipette except that an outer piece of glass tubing is fitted over the plunger tube to give it greater strength.

Although such pipettes appear to offer certain advantages, it is evident that if the tubes are kept short enough to permit convenient manipulation and to reduce danger of breakage they will not hold so much sperm as does the original Watson pipette. The smaller the diameter of the pipette, the more this criticism applies. Consideration of the quantity of sperm available in the pipette at the time of the operation in relation to success of the insemination was one reason for the exclusive use of the regular Watson pipette throughout the latter part of 1930 and for most of the work in 1931.

However, since the results in 1929, although on a small number of queens, indicate that, within the limits of the sperm available, satisfactory results can be obtained by the use of the smaller pipettes if employed under proper conditions, the question of size of pipette merits further study. For the work in 1932, consequently, pipettes were prepared which are smaller than the standard Watson pipette but larger than the pipettes used in 1929. Plungers for these new pipettes were made of nichrome wire.

USE OF AN ANESTHETIC

Although at times in previous work it had seemed that greater success might be attained through anesthetizing the queen, this was first attempted by the writer in 1930. Ether was the only agent used. A swab of cotton batting that had been dipped in ether was shoved into the glass tube holding the queen and was left there until her movements had practically ceased except for the rapid protrusion and retraction of her sting.

Twenty-four queens were operated upon with the aid of ether, 15 with the small pipette and 9 with the regular Watson pipette. (Table 1.) Of these queens 6 proved to be inseminated, 4 of these successes

being with the small pipette and 2 with the standard Watson pipette. Twelve of the other 18, or 50 per cent of the total, succumbed through balling or otherwise within 5 days after the final operation. Eight of the 12 were operated upon only once, 3 were operated upon twice on the same day, while 1 had two successive operations 14 days apart.

Of 28 queens operated upon without ether in 1930, only 4 (Nos. 30, 31, 33, and 41), about 18 per cent, were lost through natural causes within 5 days after the operation. Two queens (Nos. 46 and 47) were accidentally killed within 7 days of the insemination, while 2 others (Nos. 52 and 53) were killed for dissection purposes on the day following the insemination.

Owing to the high mortality so soon after the operation, possibly due in part to the after effects of the ether, the work for the remainder of 1930 was conducted without the use of ether. It may be that the anesthetic was not properly applied. The use of some other anesthetizing agent, such as carbon dioxide as used by Hambleton for several years in various types of work on honeybees, might prove advantageous, but in the satisfactory results reported by Watson, Mikhailoff, and Disbrowe no mention is made of the use of an anesthetic and the work of the writer in 1931 was all accomplished without it.

FILLING THE PIPETTE

Watson mentions holding the bulb of the drone on his index finger while filling the pipette. The writer finds it more convenient to retain the bulb by the forceps after pulling it loose from the drone and to fill the pipette while the bulb is being thus held. (Fig. 12.) An incision is first made in the sperm sac with fine scissors. If the incision is made at the end of the bulb containing mucus, care is taken to cut through the mucus at a point where the sac is at least as large in diameter as the pipette so that the latter will slip in easily. Sometimes there is too much mucus in a drone in relation to the sperm, or it congeals so rapidly that the pipette can not readily be forced through it to the sperm. In such cases another drone has to be obtained.

On several occasions in 1930, and more frequently in 1931, the writer cut an opening for the pipette through the "saculus" of the sperm sac described by Watson (*52*). Although in many instances it was found possible, on inserting the pipette into the "saculus," to take up large loads of sperm apparently free from mucus, this was not true in every case. The writer is therefore not yet in a position to say whether or not this method gives more success than does the method by which the pipette is inserted into the sperm from the other end of the sac without any special attempt to take up some mucus first. Success has been achieved with both methods.

MUCUS PLUG

In a previous publication (*34*) the writer mentioned that he did not consider the use of mucus essential to success in artificial insemination by the pipette method. This viewpoint, as stated earlier in this bulletin, is that most recently expressed by Watson (*52*). This does not mean that the mucus plug is held unimportant. In the writer's opinion it does play, in nature, the important rôle ascribed to it by Bishop (*5*). In the Watson method of artificial insemination

it is difficult to secure this plug, however, and a certain degree of success has been attained without it. If its use were easier, perhaps successful insemination by the pipette method might be more frequent and the degree of insemination uniformly higher. In this re-

FIGURE 12.—Filling the pipette

spect the Quinn-Laidlaw and the Malyschev methods appear to have an advantage over the Watson method.

In the writer's work with the Watson method, particularly in 1930 and 1931 when a large number of queens were treated, no special effort was made to get a mucus plug. If during the operation sperm

begins to leak back around the pipette, the exposure to the air soon causes it to harden on the surface sufficiently to keep the remainder from running out of the genital opening. Possibly this hardening is due to the presence of some mucus that has mingled with the sperm in the process of filling the pipette. In any event it seems best to provide a superabundance of sperm to take care of any wasted by leakage.

It is now the writer's usual practice to delay the withdrawal of the pipette for a few minutes after the completion of the operation and also whenever sperm begins to ooze out around the pipette. This allows the sperm to harden around the end of the pipette and thus form a sort of collar through which the pipette can be pulled out gradually without bringing the entire mass of sperm along with it. The pipette is removed by raising it slightly and loosening it from surrounding mucus with a teasing needle with bent point if this can not be done readily with the sharp end of a transferring needle.

In disregarding the mucus plug it seems essential to apply the end of the pipette squarely to the genital opening and then so to manipulate the plunger that the sperm enters without being forced back out around the end of the pipette in too large a quantity. With the improved apparatus described in this paper, this procedure is rendered much easier to achieve than under the older technic, especially since the genital opening is more readily found.

MARKING INDIVIDUALS

In any breeding experiment it is important to know as exactly as possible the genetic history of the individuals being bred from. This implies being able to distinguish between various individuals. There are other reasons why one must be able to pick out with certainty this or that bee for use in breeding work. In the first place, according to Bishop (*5*) and others, the drones must be of a certain age before they are sexually mature. Even queens are held to have optimum age limits for mating. In the second place, because of drifting, in an apiary of bees of the same race one can not be sure that a drone found in a given hive belongs to that hive. The writer has found marked drones from one hive in as many as three other hives 12 hours after marking, and further search might have shown more cases of such drifting. Other drones were found to stay in one hive over a period of weeks. Workers often make themselves at home in hives other than their own. Even when queens are confined to their hives by queen excluders, they sometimes drop to the ground and may be lost when their hives are being manipulated.

Such considerations as the foregoing render it imperative to have some means of distinguishing definitely given individuals within a hive or individuals of one hive from those of another. In the case of a queen bee this can be done easily, since her wings can be clipped to prevent flight away from the hive and a distinctive mark can be painted on her. Drones and workers present more of a problem in this respect, since there are so many more of them than queens.

One way to make sure of a drone's origin is to rear and keep it behind a queen excluder. This was proved practical in 1929 in at least one instance, and in two instances in 1930. However, the need of flight on the part of the drone is an objection to this method.

A better method, and one which allows the drone free flight throughout its life, is to give it a distinguishing mark when it emerges. Mikhailoff mentions having done this in 1929 (*25*). The writer did not begin any extensive use of such a method until 1930. As used in 1931 it consisted in marking the thorax of the drone with the number of its mother and placing on the abdomen a number to mark the week of emergence. Although this method gives the age of the drones only by weeks, and somewhat roughly at that, it can be of service in determining the relative range of age in weeks during which drones are best for use. Those desiring to know the exact age of any drone in days can give it a separate number on emergence. Queens and workers were also marked by numbering.

The method used for numbering drones, queens, and desired workers is an adaptation of that given by Von Frisch (*13, p. 42*). Ten pigments are chosen, one to represent each of the 10 digits. By combining these in dots on the thorax, any desired number can be represented. Units are represented by a dot of the proper color on the left rear of the thorax, tens by a dot on the right rear, hundreds by a dot on the left front, and thousands by a dot on the right front of the thorax. For instance, if the numeral "one" is represented by a blue pigment, bee No. 1 would carry a blue dot on the left rear of the thorax and bee No. 11 would carry a blue dot on the right rear and also one on the left rear of its thorax, bee No. 111 would be marked as described for No. 11 plus a blue dot on the left front of its thorax, and No. 1111 would carry three blue dots as for No. 111 plus one blue dot on the right front of its thorax. A similar system can be used for marking the abdomen. (Fig. 13.)

FIGURE 13.—Marked drones

DRONES

OBTAINING DRONES

It is not always easy to secure drones in sufficient quantity during the active season, especially at its beginning and end. In an endeavor to get an early supply in 1930, drones were purchased from the South about three or four weeks before their usual appearance in the apiary of the bee culture laboratory at Somerset. They were successfully united to strong colonies and consequently the season for artificial insemination opened earlier than would have been the case under natural conditions. Since, in purchasing drones commercially, it is not always possible to get the desired stock, this procedure is practical only for certain purposes.

Late in 1931 limited trials were made of stimulative feeding to induce drone rearing during a normal slackening of brood rearing.

A certain measure of success seemed to attend these efforts, since drones were present in these colonies until late in the fall. The exceptionally warm weather may have been a contributing factor.

When the first queens reared in early spring in 1932 were ready for treatment, drones were on hand from an overwintered queen which had been successfully treated the previous fall but which proved a drone layer in spring. This points to one way of securing an early supply of drones.

Prior to 1931 most of the drones used from the Somerset apiary were caught by hand at the hive entrance as they were returning from a flight, either on the wing or just as they alighted. Such drones proved more satisfactory than those taken from combs. This method was slow at times, especially when drones were scarce or when their flight was not active; so in 1931 queen-and-drone traps were put on the hives at the entrances just before the hours of greatest flight, which have been found to occur at Somerset shortly after noon. Usually more than sufficient drones were easily collected in this way, and by keeping the excess caged overnight in proper containers it was possible to have available the next morning a supply of drones suitable for the work on artificial insemination. Candy was supplied as food for the drones kept overnight and, when it seemed necessary, some workers were caged with them as attendants. Usually sufficient workers for this purpose were collected in the traps. An electric incubator provided proper temperature for the drones on cool nights. On several rainy days in 1931 the work was continued by the use of such drones when otherwise it would have been necessary to suspend operations pending better weather.

DETERMINING SEXUAL MATURITY OF INDIVIDUAL DRONES

Since in picking drones at random from a hive it is not always possible to get only those that are sexually mature even if their calendar age is marked, it is desirable to have some simple criterion as to their sexual maturity—in other words, some indication as to whether or not a drone, regardless of age in days, will furnish a supply of active spermatozoa. In experiments conducted thus far there has been found less correlation between calendar age and physiological age in drones, as far as sexual maturity is concerned, than might be anticipated. For example, some drones 2 or 3 weeks old were found without sperm or with less than was possessed by younger drones.

Statements have appeared that drones which ejaculate on decapitation are sexually mature. In 1930, of five queens (Nos. 48, 49, 50, 52, and 53) inseminated with sperm from such drones, all proved to be inseminated to a greater or lesser degree. In the operation on the other queen (No. 47) for which a record was kept, sperm from a drone not in this class was used, but the queen proved to be uninseminated. In 1931, of the 38 instances of successful insemination by the Watson method, drones which had ejaculated on decapitation were used in 25. The reaction of the drones was not recorded in 3 of these instances. For 16 of the 26 queens whose spermathecae were found clear in a post-mortem examination, such drones had also been used. The reaction of the drones used was unrecorded in only one of these instances. Since the proportion of the drones in

question to the total number used in the unsuccessful cases cited for 1931 is about the same as their proportion to the total number used in the successful cases cited for the same year, these data indicate that, for 1931 at least, it was immaterial for the accomplishment of artificial insemination which type of drone was used.

QUEEN REARING AND TESTING

EXPERIMENTS IN 1930

To economize on the quantity of bees necessary in the work, the writer in 1930 adopted the use of what he terms a "nursery colony" for rearing and keeping virgin queens, as well as for testing inseminated queen bees. This colony had no laying queen of its own. It was made up in the spring in two standard Langstroth hive bodies with 10 frames full of stores in the lower story and 10 frames full of sealed brood with adhering bees in the upper one. Until summer, when the quantity of sealed brood available decreased, frames of sealed brood were added as necessary to insure a sufficient number of young bees to carry on the work given them. This colony was fed at no time.

When queen-rearing operations were begun, one of the frames in the second hive body was replaced by a frame filled with bars for cell cups with grafted larvae. Grafts were made weekly or oftener as desired. About the third day after being sealed, the accepted cells were put in Alley nursery cages in a nursery frame and left in the second hive body. Three such frames were in this hive body most of the season, room being provided by removing the original frames as necessary.

As the season advanced a third hive body was added to the nursery colony for the purpose of taking care of the inseminated queens. When first put on, this body contained brood and honey. As queens were inseminated they were placed in California introducing cages directly on a comb of sealed brood about ready to emerge but with no other bees on it. Room was made in the hive body for these cages by removing the original frames as necessary. The California cage holds one Langstroth frame. It is made of galvanized metal except for the two sides, which are of wire screening. The comb is inserted at the top of the cage, which is provided with a sliding cover made of the galvanized metal. A 10-frame standard hive body holds 6 such cages plus 1 Langstroth frame.

Up to the close of the main honey flow, whenever an appreciable quantity of the brood in a cage had emerged, the comb, with queen and adhering bees, was removed and set in another cage similar except that one of the screened sides was replaced by excluder zinc. This new cage was then put back in the space formerly occupied by the old cage, and thus worker bees from the nursery colony and those which had emerged in the cage could intermingle and pass in and out freely. The queens were left in these cages until they began to lay or until it was apparent that the attempted insemination was not successful. When a queen began to lay, she was put in a nucleus, together with her comb from the nursery cage and a frame or two of bees from the nursery colony.

As a matter of practice, the sides made of excluder zinc were faced in the same direction in any hive body which contained more than one cage with such a side. On one occasion the nursery colony contained five queens in these modified cages, and three of the queens were laying. In addition the colony contained other queens in the regular California cages in another hive body.

Satisfactory results were obtained with this system until after the close of the main honey flow, when it was found that the bees were inclined to ball some of the queens upon gaining admittance to them through the excluder cages. This may have been due in part to the presence of a comparatively large quantity of old worker bees in the hive, a condition aggravated by the fact that sealed brood became less available from the supply colonies at this period of the season. Since the nursery colony was not fed at any time, the effect of feeding in inducing acceptance of the queens when the main honey flow had passed was not determined. After the main honey flow, therefore, the use of the cage with an excluder-zinc side was discontinued and each queen was transferred directly to her own nucleus box as soon as sufficient young bees had emerged from the comb in her screened cage to keep up the activities of an independent nucleus.

APARTMENT HIVES

In 1931, as an outgrowth of the use of the equipment just described, the writer devised what may be called "apartment" hives, which are made up of one or more compartment hive bodies. A compartment hive body is a hive body separated lengthwise into two or more divisions or compartments by wire screening. (Fig. 14.) Ordinary copper window screening has served this purpose nicely. Strips of bent tin are slipped over the edges of the screening and soldered in place. The bottoms of the hive bodies and, consequently, of each compartment, are also covered with wire screening. Each compartment holds one or more full-depth frames, and thus the total number of such compartments possible in a 10-frame hive body varies from 2 to 10. The bees are provided with an entrance to each compartment by a small hole bored through the hive body. A small block at the entrance serves as an alighting board, and over the entrance is fitted a piece of queen excluder. A separate cover of thin wood is fitted to each compartment and a standard outer cover fits over the whole.

On the basis of the size of compartments found in each, the compartment hive bodies used thus far by the writer have consisted of those with five 2-frame compartments, those with two 5-frame compartments, and those with two 3-frame compartments plus one 4-frame compartment.

The compartment hive bodies are set directly over a queen-right colony from the hive of which the inner cover has been removed. Any heat rising from the colony below will pass through the screen into the compartment hive body, and heat will also pass from compartment to compartment. These hive bodies may be tiered up. (Fig. 15.) In such a case the individual covers to each compartment except those on the top hive body can be removed, so that the screening on the bottom of the hive body above fits snugly against the top of the screening forming the walls of the divisions in the hive body

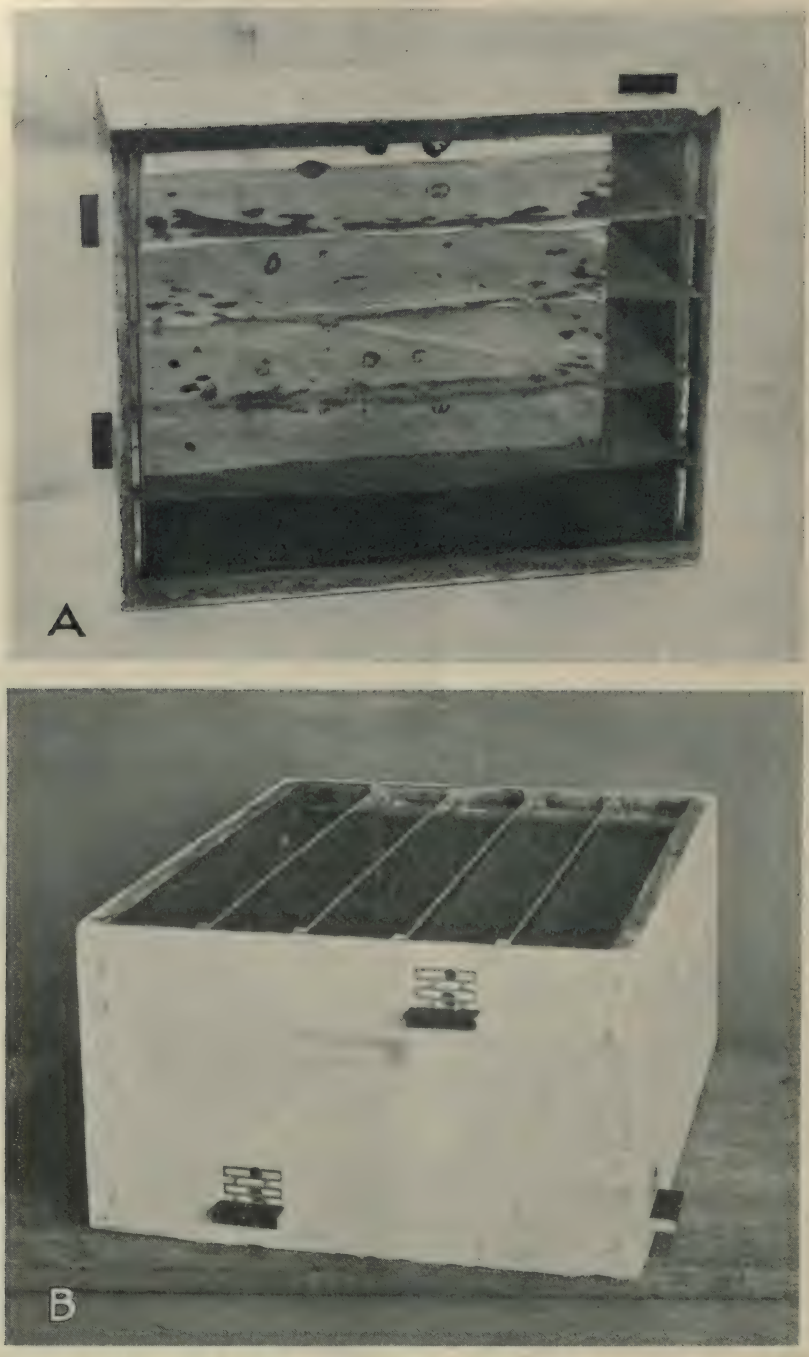


FIGURE 14.—Two views of a compartment hive body. A is without tin strips

below, preventing the passage of bees from compartment to compartment. In 1932 the largest number of hive bodies thus tiered up on one colony and manipulated by the writer was four, each containing five 2-frame nuclei. Counting the queen in the colony on the bottom, at one time there were 21 queens on this one stand, each with its own separate organization of bees. Hence the name "apartment" hive.

FIGURE 15.—A 5-compartment hive body tiered on a full-strength colony. The hive body is inside of the winter protective collar. The glass tube which extends through the collar as a passage for the bees shows at the entrance at which there is no excluder zinc. Aluminum tags used to keep records in the hive are visible on the frames

The apartment hives have proved to be as good as, or even better than, the ordinary type of nucleus during the robbing season, since the bees for the most part have defended each compartment well. A little care must be exercised, of course, in opening the compartments at this season. Little trouble was experienced in 1931 by bees from one compartment running into a neighboring compartment when adjoining compartments were exposed for purposes of manipulation. In 1932, in the case of tiered-up compartment hive bodies, all compartments that were not being manipulated were kept covered. It may be that all bees in the apartment hive have more or less of a common hive odor. In any event the bees in each compartment

seem to remain there without any more than normal drifting elsewhere, even though the entrances were often not very far apart.

The queens are introduced into the compartments by means of a Miller introducing cage. The workers are usually denied access to the candy for three days by fastening a piece of tin across the candy hole. Frames of emerging brood are added to the compartments as necessary to insure the presence of young bees when a queen is being introduced or at other times.

The use of apartment hives is recommended for only those beekeepers who will give them the proper care and attention.

WINTERING IN APARTMENT HIVES

An experiment to winter queen bees in apartment hives was undertaken for the winter of 1931 and 1932. Two compartment hive

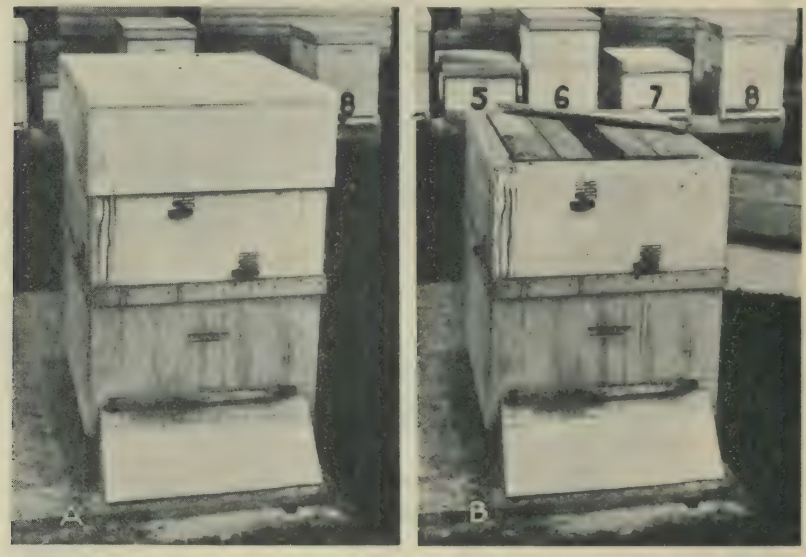


FIGURE 16.—Wintering in apartment hives: A, Apartment hive consisting of a 5-compartment hive body over a normal colony; B, telescope cover and tray removed to show individual inner covers of compartments

bodies, each with five 2-frame nuclei, two with two 5-frame nuclei, and one with two 3-frame nuclei plus one 4-frame nucleus were chosen. Each of the five compartment hive bodies was over a 10-frame colony in a double-wall hive, and a packed double-wall collar was fitted around it. A tray of sawdust covered the top of each hive, and over this a telescope cover was slipped. A hole drilled through the collar, into which glass tubing was fitted, connected the entrance of each compartment with the outside. A piece of queen excluder was placed over the outer opening of the tube in some cases. (Fig. 16.)

The winter was milder than is common in the region of Somerset, Md., but since there was consequently more flight activity than usual for this period of the year the weather can not be considered in itself as having been conducive to successful wintering. Never-

theless, the condition on March 1, 1932, of all those nuclei which had plenty of bees on November 1, 1931, was highly satisfactory, with the exception of one 5-frame nucleus. This nucleus, which contained queen No. 51, appeared to have sufficient bees on entering winter, but on February 10 it was queenless and only a handful of living bees remained. Of the 17 experimental nuclei, this 5-frame nucleus and a 2-frame nucleus were the only ones not strong enough in the spring to carry on brood rearing successfully. Perhaps the bees on hand in each nucleus in the fall were somewhat older than was thought. Each of the 10-frame colonies below the compartment hive bodies wintered excellently. The especially strong condition of some of the 2-frame nuclei was a pleasant surprise and showed clearly the value of this method for wintering with a minimum of bees the queens being tested, provided there has been no neglect in insuring the presence of sufficient young bees in the nuclei by the beginning of winter.

QUEEN REARING IN 1931

In line with the other efforts to reduce the number of worker bees and the labor required in the work, all queen cells upon being sealed are put in Alley nursery cages and then placed in an electric incubator and left there at brood-rearing temperature until they hatch. This incubator has glass sides, top, and door, and has sufficient room inside to hold two hive bodies. For queen-rearing purposes, however, this space is divided by a number of shelves to hold the nursery cages. The incubator is located in a building adjacent to the apiary.

An attempt was made in 1931, but somewhat unsuccessfully, to keep virgins in the incubator after hatching. Fresh candy was given for food, and worker bees were provided as attendants. On one occasion all of about 50 virgins so left died within three or four days after emergence. Thereafter the newly emerged virgins were given fresh candy and their cages placed in nursery-cage frames. These in turn were placed in a super directly above the brood nest of a queen-right colony, but separated from it by a queen excluder. Frames of sealed brood, taken from the brood nest below, were placed next to the nursery-cage frame. The chief disadvantage of this method is the tendency of the bees to desert the caged virgins when the weather becomes cool.

In 1932 virgins were successfully kept in early spring in 3-frame queenless nuclei in apartment hives. A special frame was used which consisted of an old brood frame with enough comb cut out of the lower portion to allow the insertion of two nursery cage bars from a standard Alley nursery frame.

In 1931 queen-rearing operations were often conducted with larvae from several queens at once. It was desired to have larvae from any one queen reared by only one colony. However, to have maintained a separate colony for rearing the larvae transferred from each of these queens, as described in the work for 1930, would have taken too much time and too many bees; hence use was made of 2-frame nuclei in compartment hive bodies. Each nucleus was kept strong in young bees. The lower portion of one comb in each compartment was cut away and a removable cell bar was inserted next to a thin

strip of wood, which in turn was securely fastened next to the cut edge of the comb. Good results were obtained from these queen-rearing nuclei. In 1932, 3-frame compartments were used instead of the 2-frame compartments, since it is easier to maintain sufficient bees in the larger nuclei.

Frequently it is desirable to carry on transferring operations on cold, rainy, or dark days, or during the robbing season. In order to do this the writer devised a wooden support to hold a brood frame at a convenient angle on a stand during the process. The stand is located in the same room as the electric incubator. With a small movable electric lamp in one hand and the transferring needle in the other, transferring is accomplished under convenient conditions.

HIVE RECORDS

For keeping records within the hive concerning cell bars, queen cells, and queens, tags cut out of aluminum tape and bearing numbers or letters, or both, have proved useful. Numbers and letters can quickly be marked on such tags by a metal stamping outfit, or by scratching with a nail or other sharp instrument. The tags are easily fastened to top bar, cell cage, or queen cage by a thumb tack. The number assigned to any queen and her race or origin, as well as dates of her birth, insemination, first egg laying, and the like, may be thus recorded. In the case of cell bars, the number or origin of the queen from which the larvae are derived, the date of grafting, and the date of first sealing of cells on the bar can be placed on the tags. (Fig. 15.)

When there are many nuclei to be looked after, the use of thumb tacks on the outside of the hive will be found helpful as a means of indicating quickly those colonies needing special attention. Thus an absence of thumb tacks on a compartment may indicate that all was normal within at the last examination. One tack may mean that the queen has been successfully introduced, two tacks may have some other meaning assigned it, and so on. The position of the tacks may be given a certain meaning. The advantage of the tacks is that they are easily withdrawn but stay where placed unless forcibly removed.

VIABILITY OF SPERMATOZOA

Certain experiments performed in Europe (*35*, *36*) indicate that spermatozoa from drones may remain alive at least a number of hours in various electrolytes. Bishop (*5*) has reported that spermatozoa in a salt solution mounted on a slide were still alive after two hours' contact with ice. In order to determine how long honeybee spermatozoa would remain alive under conditions somewhat similar to those in the glass pipette, the writer mounted some on a slide with a cover glass. Under these conditions the spermatozoa at times were found motile more than three hours later at room temperature.

Of particular interest in this connection are the cases of queens Nos. 29 and 86, used in the work for 1931. One of these queens (No. 29), after an operation which seemed normal and satisfactory, was found dead in her Miller introducing cage the next morning at 8.30. A post-mortem examination under the microscope was not made until 11 a. m., at which time her spermatheca was estimated to be 50

per cent filled with sperm and an abundance of live spermatozoa were observed in highly active motion. Even more striking was the case of queen No. 86, which was found dead at 3 p. m. on September 1. She was in an Alley nursery cage in a colony at that time and was left there until the next day at 11 a. m., when a microscopic examination of her spermatheca indicated that it was 75 per cent filled with sperm. A great abundance of living spermatozoa was seen. It is to be noted that these spermatozoa had survived 20 hours in the spermatheca of a dead queen in a cage between the frames of a hive.

Certain results given by Bishop (*5*, *p. 247*) are in line with the findings presented for these two queens. On one occasion he subjected a "fertile" queen to a temperature 3.6° F. (2° C.) below freezing, for 15 minutes. He states that none of her eggs laid subsequently were found to be infertile.

SUCCESSIVE INSEMINATIONS

The writer has given elsewhere (*39*) a review of the numerous instances in beekeeping literature on the multiple matings of queen bees. That insemination results when the sperm from different drones is introduced into queen bees on successive occasions not on the same day has been indicated in work both by Watson (*52*) and by the writer. In 1930 the writer attempted this on three occasions and had good results in two of them. (Table 1.) For one of the successful instances the interval between operations was 2 days, while for the other one it was 15 days; for the unsuccessful case it was 14 days. In addition seven queens were given two operations in one day, but in only one case was the treatment successful. Three of the queens were found to have clear spermathecae, and three disappeared.

In 1931, 33 queens were operated upon twice by the Watson method, and 8 of these in turn were operated upon three times. (Table 2.) Sixteen of the 33, or about 48.5 per cent, proved to be inseminated. This is to be compared with 34.4 per cent of ascertained success for the 64 queens operated on only once, 22 of these having been found inseminated. In the case of 14 of the 33 queens the second operation was performed on the same day as the first, while a third operation was performed later on 3 of these, but all 3 disappeared. Of the remaining 11 queens operated on twice in the same day, 4 proved to be inseminated, 4 were lost, and 3 had clear spermathecae.

Of the other 5 queens which were given a third operation, 3 proved to be inseminated and the other 2 disappeared. In one of these successful cases (No. 86) sperm was found so massed in the queen's spermatheca that the degree of insemination was estimated to be at least 75 per cent. Queen No. 53 was found to be somewhat less inseminated, while the other case (No. 88) was classed as less than 10 per cent successful.

The results for 1930 are not comparable with those for 1931 because of the use of ether in some cases. The results for 1931, although not conclusive in themselves, seem to be in line with Watson's statement (*52*) that repeated inseminations increase the degree of success. In describing his work for 1927 (*51*), Watson mentions that he operated on some queens from 1 to 10 times.

It is possible that many of the queens that disappeared in 1931 before any check could be made as to their insemination, as well as many of those that were found dead in the cage, may have been lost in attempts to get out through the excluder to take a mating flight. That many of the queens found dead in the nuclei had tried to get out or had suffered rough treatment from their bees seems evidenced by the fact that the painted markings had been rubbed off the thorax in nearly all cases. It seems of significance in this connection that practically all those queens which laid eggs were readily accepted by the nuclei in which they were introduced.

MIXING SPERM FROM DIFFERENT DRONES

Without following the genetic composition of succeeding generations, it is hard to say in the case of insemination from the sperm of different drones on successive days whether or not the sperm from each drone was active. In the case of 8 of the queens operated upon in 1930 the sperm from more than one drone was loaded into the pipette at one filling. Seven of these operations were successful. Sperm from 2 drones was used in 5 cases, 4 of which proved successful; sperm from 3 drones was used for 2 queens, and each of these queens was found to be inseminated. In one of these instances all the first brood sealed proved to be worker. For the eighth queen sperm from 5 drones was used, and this operation was also successful.

In 1931 the sperm from more than one drone was loaded into the pipette in the operations on 29 queens. Eleven of these queens proved to be inseminated. On two occasions the sperm from 3 drones was used, and in each case a successful insemination resulted. In no instance was the sperm from more than 3 drones employed.

The foregoing examples indicate that a mixture of sperm from different drones does not destroy the vitality of all the spermatozoa at least. In each case the pipette was loaded by taking up the sperm from the drones in succession. It happened that all the drones used for any one operation came from the same hive.

In his 24 successful inseminations in 1929, Mikhailoff (*25*) used sperm from 2 or more drones for 22 of the queens. For 1 queen he reports the use of only 1 drone, while for 1 he does not give the number. In a later article (*28*) he states that he used the sperm from 2 to 4 drones for every queen.

OPTIMUM AGE OF QUEEN FOR ARTIFICIAL INSEMINATION

It is frequently stated in beekeeping books that the queen usually mates early in life and that if she delays more than three weeks she is apt to become a drone layer. Thus, Phillips (*40, p. 49*) gives the normal age of the queen for mating as 5 to 8 days. In a compilation made by Armbruster (*4*) of data from mating stations covering six years, 9 days was the age of the queen at which the greatest number of matings was found to occur. If these conditions hold in natural mating, it might be expected that more success would be attained in artificial insemination with queens only a few days old than with older queens.

Mendel (*19, p. 149; 54*), however, held that a queen remains capable of being inseminated up to the twenty-eighth to the thirtieth

day after emerging, and that for some queens this time limit is even longer. Likewise, although in the data by Armbruster (*4*) on natural matings of the queen bee the earliest age at which any of the queens mated was 3 days, the oldest age is given as 32 days. The queens successfully operated upon in 1929 by Mikhailoff (*26*) ranged from 7 to 29 days in age, while Watson (*49*) reports that he has been successful in the artificial insemination of queens even 37 days old.

In 1930 a record of the data of emergence and of attempted artificial insemination was kept by the writer for 43 queens which were operated on only once or only once plus a second operation within two days of the first, and in 1931 for 82 queens which were operated on only once or, in some instances, once again within one day of the first operation, making a total of 125 queens. As a matter of fact, only 1 of the 43 queens listed for 1930 (No. 44) received a second operation, while 5 of the 82 listed for 1931 (Nos. 8, 14, 46, 86, and 90) received a second operation. Queen No. 86 received a third operation. In Table 3, which gives the results obtained from queens of various ages, these six queens have been considered as receiving their successful operation on one occasion, since the time interval between the operations is small. Of these 125 queens, 47 proved to be inseminated.

TABLE 3.—*Success attained with queens operated on in 1930 and 1931 only once or within two days of a preceding operation in age period specified*

Age of queens	Total queens inseminated	Successful operations	
	Number	*Number*	*Per cent*
1 to 8 days	59	14	23.7
9 to 16 days	41	14	34.1
17 to 24 days	20	15	75.0
25 to 32 days	5	4	80.0

From these results it is apparent that the greatest degree of success was attained by using queens at least 17 days old. The total number of queens (100) under 17 days of age which were used, however, was four times as large as the number (25) of those which were 17 days old or over, but the percentage of success with the younger queens was only 28 as compared with 76 for the older queens. It is interesting to note that No. 47, operated on in 1931, even though mated when 29 days old, proved to be one of the most prolific layers of worker eggs of the queens mated that year. In 1930 two queens were successfully mated at the age of 31 days. On the other hand, in 1931 a queen 1 day old was successfully inseminated. The data presented here, although based on a small number of cases over 17 days of age, indicate that the age limit at which queens can be inseminated artificially is higher than that commonly accepted as the limit for natural insemination.

SUCCESSION OF GENERATIONS

Regardless of any method for inseminating queen bees at will or of any method for carrying queens through either the active or the inactive season with a minimum of labor, time, and equipment, suc-

cess in breeding the honeybee and other forms is dependent upon a third factor—upon having a succession of generations. The writer has been successful in the first factor mentioned since the beginning of his work in this field, while, as for the second factor, an artificially inseminated queen was wintered over in the first year of the work. However, F_1 queens from artificially inseminated mothers were not obtained until 1930. These were all reared from one mother. Six of them were successfully operated upon that year and from one of these an F_2 queen was reared. This queen was born too late for mating that year, however.

In 1931, as already stated, F_1 queens were reared from eight artificially inseminated queen bees. Unfortunately none of these was reared before July, and since August was marked by an unusual scarcity of drones, the inseminations during the latter part of the season were somewhat restricted both as to number of attempts and as to degree of success.

Of the 97 queens used in the work with Watson's method in 1931, 32, or practically one-third, were F_1 queens. Workers of the F_2 generation were obtained from one of these (No. 78) in October. It was then so late in the season that no attempt was made to rear F_2 queens from this queen, but she was still alive at the beginning of winter. Insemination in the case of 6 others of the 32 was determined by a microscopic examination of their spermathecae, making a total of 7 of the F_1 queens, or 21.9 per cent, which were found to be inseminated. Eight of the remaining 25 gave no evidence of insemination on a post-mortem examination; 15 disappeared; while the other 2 (Nos. 77 and 92), inseminated late in the fall, entered the winter season without having commenced egg laying.

In the work as conducted in 1932 there was no difficulty in obtaining a succession of generations. Of four successive generations of queens reared in that year from a certain strain, the first three had been successfully inseminated by the Watson method before September, as evidenced by the rearing of virgins and workers. Certain other strains were carried three generations, and a number were carried two. Under ordinary conditions five or six generations should be secured readily in a season such as characterizes Somerset, Md. Under optimum conditions during the active season one generation a month is not out of the question, although one every five or six weeks appears satisfactory at present.

SUMMARY

In breeding the honeybee under controlled conditions either natural or artificial insemination can be used. The only feasible method thus far developed which makes use of natural insemination is that of using mating stations. An important objection to this method is the difficulty of being absolutely sure that no wild swarms or colonies kept by beekeepers exist within a radius which would make possible crossings other than those desired.

For absolute certainty as to drone and queen, artificial insemination can be employed. Two main methods have been developed for accomplishing artificial insemination: (1) Removing the organ containing the sperm from the drone and placing it in proper position

in the queen to accomplish insemination, as done by Malyschev and by Quinn-Laidlaw; and (2) removing the sperm completely from the drone organ and then introducing it within the queen, as done by Watson. Thus far only the Watson method has been repeatedly used with success in the hands of others.

The technic originally described by Watson has been modified by the use of new instruments and methods. Methods have also been developed to use a small number of bees and to reduce the quantity of equipment required in rearing and testing queens used in breeding work.

Spermatozoa will remain alive under the cover glass or in the spermatheca of a dead queen for several hours at ordinary summer temperature.

Successive artificial inseminations of a queen, at least before she begins egg laying, can be made with good results.

Sperm from different drones can be mixed together without apparent effect on some of the spermatozoa at least.

Worker brood was reared from a queen inseminated when 29 days old. In 1930 and 1931 greater success was had with queens 17 days of age or older than with younger queens.

A succession of generations of the honeybee is possible through the use of artificial insemination. Four generations is the largest number yet obtained at Somerset, Md., in one season, although under optimum conditions it should be possible to obtain a generation a month during the active season.

LITERATURE CITED

(1) ANONYMOUS.
1928. LOUISIANA MEETING A SUCCESS. Amer. Bee Jour. 68: 464–465.

(2) [ABUSHADY, A. Z.]
1931. (EDITORIAL NOTE.) Bee Kingdom 2: 35.

(3) ALPATOV, W. W.
1928. [CONTROLLED MATING OF HONEYBEE QUEENS.] Pchelovodnoye Delo 8: 344–349. [In Russian.]

(4) ARMBRUSTER, L.
1927. DIE BIENENZÜCHTUNG IM JAHRE 1926. Jahrb. Wiss. u. Praktische Tierzucht. 19 (Teil 2, Kleintierzucht): 182–188.

(5) BISHOP, G. H.
1920. FERTILIZATION IN THE HONEY-BEE. I. THE MALE SEXUAL ORGANS: THEIR HISTOLOGICAL STRUCTURE AND PHYSIOLOGICAL FUNCTIONING. II. DISPOSAL OF THE SEXUAL FLUIDS IN THE ORGANS OF THE FEMALE. Jour. Expt. Zool. 31: 225–[266], 267–286, illus.

(6) CALE, G. H.
1926. THE FIRST SUCCESSFUL ATTEMPT TO CONTROL THE MATING OF QUEEN BEES. Amer. Bee Jour. 66: 533–534.

(7) CHRIST, J. L.
1798. ANWEISUNG ZUR NÜTZLICHEN UND ANGENEHMSTEN BIENENZUCHT. . . . Aufl. 3, 372 p., illus. Leipzig.

(8) DALTON, J.
1930. SOUTHERN STATES CONFERENCE AT BATON ROUGE. Amer. Bee Jour. 70: 169, 191, 198.

(9) DISBROWE, H. B.
1929. ARTIFICIAL INSEMINATION OF QUEENBEES. Beekeeper 37: 128.

(10) ———
1929. ARTIFICIAL INSEMINATION OF QUEENBEES AT ONTARIO AGRICULTURAL COLLEGE. Amer. Bee Jour. 49: 599.

(11) ———
1931. CONTROLLED MATING OF QUEEN BEES. Beekeeper 39: 53–54.

(12) DZIERZON, J.
1849. NEUE VERBESSERTE BIENEN-ZUCHT. . . . Aufl. 3, 304 p., illus. Neisse.

(13) FRISCH, K. VON
1931. AUS DEM LEBEN DER BIENEN. Aufl. 2, 159 p., illus. Berlin.
(14) GOLDI, R.
1914. DIE WIRKSAMKEIT VON HERRN ULRICH KRAMER. Schweiz. Bienen-Ztg. 37: 396–401.
(15) HAMBLETON, J. I.
1929. BEE BREEDING BY ARTIFICIAL INSEMINATION DONE EXPERIMENTALLY. U. S. Dept. Agr. Yearbook 1928: 138–141.
(16) HOWARD, C. W., AND FRANCE, L. W.
1917. FERTILIZATION OF QUEEN BEES. Amer. Bee Jour. 57: 376–378.
(17) HOWARD, L. O.
1908. REPORT OF THE ENTOMOLOGIST FOR 1908. U. S. Dept. Agr. Ann. Rpt., 47 p.
(18) HUBER, F.
1814. NOUVELLES OBSERVATIONS SUR LES ABEILLES. Ed. 2, 2 v. Paris, Geneva.
(19) ILTIS, H.
1924. GREGOR JOHANN MENDEL. LEBEN, WERK UND WIRKUNG. 426 p., illus. Berlin.
(20) JAGER, F., AND HOWARD, C. W.
1914. THE ARTIFICIAL FERTILIZATION OF QUEEN BEES. Science (n. s.) 40: 720.
(21) KRAMER, U.
1930. DIE RASSENZUCHT DER SCHWEIZER IMKER. Aufl. 7, revised by M. Jüstrich. 208 p., illus. Aarau.
(22) MCLAIN, N. W.
1887. REPORT ON EXPERIMENTS IN APICULTURE. U. S. Dept. Agr. Rpt. Ent. 1886: 583–592, illus.; also in Amer. Bee Jour. 23: 567–569, 1887.
(23) MALYSCHEV, S. I.
1924. [ARTIFICIAL INSEMINATION OF THE HONEYBEE.] Chelovek i Priroda 1924: 579–586. [In Russian, original not seen.]
(24) MARLATT, C. L.
1930. REPORT OF THE CHIEF OF THE BUREAU OF ENTOMOLOGY. U. S. Dept. Agr. Ann. Rpt., 76 p.
(25) MIKHAILOFF, A. S.
1929. [THE ARTIFICIAL INSEMINATION OF QUEEN BEES.] Opitnaia Paseka 1929: 10–22, illus. [In Russian.]
(26) ———
1930. [SUCCESSES AND FAILURES IN THE ARTIFICIAL INSEMINATION OF QUEENS IN THE HONEYBEE.] Opitnaia Paseka 1930: 15–19, illus. [In Russian.]
(27) ———
1931. INSTRUMENTAL INSEMINATION OF QUEEN BEES AT THE TULA STATION. Amer. Bee Jour. 71: 72.
(28) ———
1931. ÜBER DIE VERERBUNG DER WEISSÄUGIGKEIT BEI DER HONIGBIENE (APIS MELLIFERA). Ztschr. Induktive Abstam. u. Vererbungslehre 59: 190–202.
(29) NEWELL, W.
1915. INHERITANCE IN THE HONEY BEE. Science (n. s.) 41: 218–219.
(30) NOLAN, W. J.
1925. DEVELOPMENT OF QUEEN REARING IN THE UNITED STATES. VIIth Internatl. Cong. Beekeepers Sept. 1st to Sept. 4th 1924 [Proc.]: 298–307. In French in same volume p. 83–95; also in L'Apiculteur 70: 143–148; 177–181; 242–246. 1926.
(31) ———
1928. SEASONAL BROOD-REARING ACTIVITY OF THE CYPRIAN HONEYBEE. Jour. Econ. Ent. 21: 392–403, illus.
(32) ———
1929. SUCCESS IN THE ARTIFICIAL INSEMINATION OF QUEEN BEES AT THE BEE CULTURE LABORATORY. Jour. Econ. Ent. 22: 544–551.
(33) ———
1929. ARTIFICIAL INSEMINATION: WATSON METHOD IS DESCRIBED. Amer. Honey Producer 3 (4, 5, 6): 3–4.
(34) ———
1929. USPECHY V UMELÉM OPLOZENI VČELICH MATEK. Včela Moravská 72 (30): 398–401, illus. Transl. into Czech by Š. Soudek.

(35) NOLAN, W. J.
1929. THE BERLIN CONFERENCE OF THE APIS CLUB. Amer. Bee Jour. 69: 541–543, 568–569.
(36) ———
1929. BEEKEEPERS OF MANY NATIONS MEET. Gleanings Bee Cult. 57: 640–642.
(37) ———
1930. BEE RACES VARY IN PHYSICAL CHARACTERS AND IN BEHAVIOR. U. S. Dept. Agr. Yearbook 1930: 128–130, illus.
(38) ———
1930. RACES OF THE HONEYBEE. Penn. Beekeeper 5 (No. 1): 1–4.
(39) ———
1932. MULTIPLE MATINGS OF THE QUEEN BEE. Rpt. Md. State Beekeepers' Assoc. 23rd Annual Meeting, Baltimore, January 7, 1932: 20–34.
(40) PHILLIPS, E. F.
1931. BEEKEEPING; A DISCUSSION OF THE LIFE OF THE HONEYBEE AND OF THE PRODUCTION OF HONEY. 490 p., illus. New York.
(41) PRELL, H.
1927. DIE KÜNTSLICHE BEFRUCHTUNG DER BIENENKÖNIGIN. Leipziger Bienen-Ztg. 42: 225–230; also in Märkische Bienen-Ztg. 17: 236–241; and Cong. Internatl. Zool. (1927) 10 (pt. 1): [455]–462. 1929.
(42) ———
1929. JAHRESBERICHT 1928 ÜBER DIE BIENENKUNDLICHE TÄTIGKEIT IM ZOOLOGISCHEN INSTITUT DER FORSTLICHEN HOCHSCHULE THARANDT. Leipziger Bienen-Ztg. 44: 229–231.
(43) QUINN, C. W.
1923. HAND-FERTILISATION OF QUEENS. Bee World 5: 75.
(44) RÉAUMUR, R. A. F. DE
1740. MEMOIRES POUR SERVIR À L'HISTOIRE DES INSECTES. 6 v., Paris.
(45) SHAFER, G. D.
1917. A STUDY OF THE FACTORS WHICH GOVERN MATING IN THE HONEY BEE. Mich. Agr. Expt. Sta. Tech. Bul. 34, 19 p., illus.
(46) SWAMMERDAM, J.
1758. THE BOOK OF NATURE; OR, THE HISTORY OF INSECTS: REDUCED TO DISTINCT CLASSES, CONFIRMED BY PARTICULAR INSTANCES, DISPLAYED IN THE ANATOMICAL ANALYSIS OF MANY SPECIES . . . English transl. from the Dutch and Latin original editions by Thomas Flloyd. Rev. and improved . . . by John Hill. 2 pts., illus. London.
(47) WANKLER, W.
1924. DIE KÖNIGIN, SELBSTERLEBTES FÜR JÜNGER DER NEUZEITLICHEN WEISELZUCHT. Aufl. 4, stark verm. und umgearb., 122 p., illus. Freiburg.
(48) ———
1927. DIE KÜNSTLICHE BEFRUCHTUNG DER BIENENKÖNIGIN. Bienen-Vater 59: 261–265; also in report of 65 Wanderversammlung der Bienenwirte deutscher Zunge, 6 p. Leitmeritz.
(49) WATSON, L. R.
1927. CONTROLLED MATING OF QUEENBEES. 50 p., illus. Hamilton, Ill.
(50) ———
1927. CONTROLLED MATING IN THE HONEYBEE. Iowa State Apiarist Rpt. 1927: 36–41.
(51) ———
1928. CONTROLLED MATING IN HONEYBEES. Quart. Rev. Biol. 3: 377–390, illus.
(52) ———
1929. NEW CONTRIBUTIONS TO THE TECHNIQUE OF INSTRUMENTAL INSEMINATION OF QUEENBEES. Jour. Econ. Ent. 22: 944–954, illus.
(53) ———
1929. INSTRUMENTAL INSEMINATION OF QUEENBEES. Internatl. Cong. Ent. (1928) Trans. 4: [976]–977.
(54) ZIWANSKY, F.
1872. BERICHT ÜBER DIE MONATVERSAMMLUNG AM 4 APRIL, 1872. Die Honigbiene von Brünn 6: 65–67.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	ARTHUR M. HYDE.
Assistant Secretary	R. W. DUNLAP.
Director of Scientific Work	A. F. WOODS.
Director of Regulatory Work	WALTER G. CAMPBELL.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel and Business Administration.	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Solicitor	E. L. MARSHALL.
Bureau of Agricultural Economics	NILS A. OLSEN, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	PAUL G. REDINGTON, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Office of Cooperative Extension Work	C. B. SMITH, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology	C. L. MARLATT, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.*
Forest Service	R. Y. STUART, *Chief.*
Bureau of Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	WILLIAM A. TAYLOR, *Chief.*
Bureau of Plant Quarantine	LEE A. STRONG, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Weather Bureau	CHARLES F. MARVIN, *Chief.*

This bulletin is a contribution from

Bureau of Entomology	C. L. MARLATT, *Chief.*
Division of Bee Culture	J. I. HAMBLETON, *Senior Apiculturist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1932

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents